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ARTICLE

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ABSTRACT
Racial and gender disparities persist in science, technology, engineering, and mathematics (STEM) despite decades of mentoring interventions to improve recruitment and retention. We offer a STEM Mentoring Ecosystems (STEM-ME) framework to better situate, understand, and advance the mentoring systems that are needed to bring about change. We outline a STEM-ME framework, which we argue require shifts in perspective, expanding beyond individual mentees and mentors, as well as specialized mentoring programs, to analyze the mentoring ecosystems within which STEM mentoring operates. Next, we use this framework to examine and critique current mentoring infrastructure and mentor preparation; this includes an inventory of assets and gaps as pertaining to faculty, students, and administrators as mentors. Then, we examine how silos could be more synergistic, which new structures are needed, who and where the ecological stewards are, and implications for systems change. How the STEM-ME framework informs future empirical research and practice is discussed.

KEYWORDS
Mentoring; STEM; ecosystems; higher education; equity

While STEM fields have demonstrated some progress with regard to the diversity reflected in the workforce and associated academic pathways, serious racial and gender disparities persist (National Academies of Sciences, Engineering, and Medicine, 2016). For example, Blacks and Hispanics constitute an estimated 32% of the 2018 U.S. population, yet only 5% and 6% of science and engineering occupations (National Academy of Sciences, National Academies of Sciences, Engineering, and Medicine, 2011; National Science Foundation [NSF], 2017; United States Census Bureau, 2018). Women across racial groups remain underrepresented in STEM fields including engineering and computer science; women comprise less than 20% of students in computer science, while African American women and Latinas constitute less than 4% and 2%, respectively

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(Whitney, Gammal, Gee, Mahoney, & Simard, 2013). At the faculty level, approximately 10% of the women faculty in STEM – which constitutes just over one-third of the faculty overall – and 7% of male faculty in STEM are Black and/or Hispanic/Latinx (National Science Foundation [NSF], 2017). The underrepresentation of women and racial minorities only worsens at advanced levels of faculty and administration (Whittaker, Montgomery, & Martinez Acosta, 2015).

Many factors contribute to this multilayered problem, including an inhospitable climate for minoritized groups (Griffin, 2013; Johnson, 2012), and histories of exclusion of particular racial, ethnic, and other demographic groups (Girves, Zepeda, & Gwathmey, 2005; Harper, 2012; Hurtado, Milem, Clayton-Pedersen, & Allen, 1998; Moss-Racusin, Dovidio, Brescoll, Graham, & Handelsman, 2012; Sethna, 2011; Zambrana et al., 2015). For decades, efforts at national and local levels have devoted energy to creating interventions that improve diversity, inclusion, and retention in STEM. Mentoring, whether as a program or as an embedded feature of another initiative, has been proposed as one promising strategy in this regard, for both recruiting and retaining individuals from underrepresented groups (e.g., Griffin, Perez, Holmes, & Mayo, 2010; Packard, 2015).

Mentoring has been defined as a process in which an experienced individual – the mentor – educates, guides, counsels, leads, or assists a less experienced individual – the mentee, protégé, or student (Crisp & Cruz, 2009; Eby, Rhodes, & Allen, 2007; National Academies of Science, Engineering, and Medicine; National Academies of Sciences, Engineering, and Medicine, 2019). In this work, we define mentoring as a developmental relationship that is intended to support the growth of the learner or protégé forward, involving a constellation of mentors with different assets and skills. Researchers have demonstrated that when effectively implemented, mentoring can help students overcome barriers that impede their success (Pfund, Byars-Winston, Branchaw, Hurtado, & Eagan, 2016). Programs may connect students to mentors (e.g., faculty, staff, industry professionals, peers) and strengthen students' technical or research mastery (Linn, Palmer, Baranger, Gerard, & Stone, 2015; Packard, Marciano, Payne, Bledzki, & Woodard, 2014), both of which contribute to feelings of belonging. Mentoring has been consistently predictive of long-term success in STEM, whether measured by completion of a degree, graduate school enrollment, or attainment of longer-term, career-related outcomes (Pritchard & Grant, 2015; Stolle-McAllister, Sto Domingo, & Carrillo, 2011; Woodcock, Hernandez, & Schultz, 2016).

Indeed, we acknowledge that research on STEM mentoring has advanced significantly in the past two decades, specifically regarding metrics, attributes, and characteristics (Eby et al., 2007; Ensher & Murphy, 2011; Pfund et al., 2016). Even so, much of the research has been generated from an analysis of specialized programs (Jones, Barlow, & Villarejo, 2010; Stolle-McAllister et al., 2011; Whittaker & Montgomery, 2012; Wilson et al., 2012), student experiences (Aikens et al., 2016; Saddler, 2010), or mentor experiences (Dolan & Johnson, 2009; Whittaker & Montgomery, 2012). As scholars of mentoring who come to this work from different disciplinary perspectives (engineering/engineering education, education/psychology, and biology), and whose work has focused on different aspects of mentoring through the career trajectory (students, faculty, administrators), we also appreciate how our own work is located in various silos, whether disciplinary, career stage, or otherwise. Even though some of this is a function of how knowledge is traditionally distributed through disciplinary journals and professional organizations, the outcome is that many who work on mentoring are relatively uninformed by others' work with similar goals.

Further, much of the rhetoric around improving mentoring promotes an ineffective strategy to system change. When using mentoring programs, there is an assumption that adding more programs incrementally benefits more students, as if the programs can serve to patch problems in the STEM pipeline (e.g., Schultz et al., 2011). However, this approach does not fundamentally change the system within which programs operate. This change management approach is what Rowland (2017) referred to as to 'layer change onto a system,' rather than to 'create movement' through attempting to 'change the system from its source' (p. 154).

Indeed, over multiple decades, we observe that specialized programs still operate, in many contexts, in contrast to the daily practices of an institution or field. O'Meara, Griffin, Nyunt, and Lounder (2019) referred to this specialized location as a supportive 'third space' that creates new rules and norms outside of the status quo in STEM (p. 205). How do we bring more systemic changes so that effective mentoring is truly an embedded, fundamental part of the fabric of STEM fields and a collective responsibility?

In this conceptual work, we propose a STEM mentoring ecosystems (STEM-ME) framework to examine and critique the mentoring ecosystems within which STEM mentoring work operates. Current STEM mentoring ecosystems do not appear positioned to produce the kinds of systematic mentoring that STEM fields actually need. Mentoring can be sustained and scaled within an ecosystem that supports the practice as an embedded feature of interactions among its collective participants; otherwise, such activity is likely to be inconsistent or vulnerable. We need to invest in the intentional cultivation of STEM mentoring ecosystems so that beneficial mentoring is more prevalent, consistent, and sustained. This, we argue, is crucial to facilitate transformation of a STEM academic system that has, to date, remained resistant to change, especially when considering advancing diversity and equity goals.

In the process of developing a STEM mentoring ecosystems (STEM-ME) framework, we started with an ecosystems framework in order to reveal holistic details and insights about STEM mentoring ecosystems. As a result, the framework itself provides a lens through which to make sense of prior and future work on mentoring, including mentoring processes, structures, and contexts for capacity-building. Subsequently, researchers may use the framework to guide future empirical studies to provide a better understanding of mentoring ecosystems.

In this article, we outline the developed STEM-ME framework and use it as a lens to understand and examine the STEM mentoring ecosystems reflected within existing mentoring literature, knowledge, and resources. Specifically, we critique the current state of infrastructure for mentoring and how mentors are prepared; this includes resourcing for faculty, students, and administrative leaders as mentors. Next, we examine how silos of activity could be more synergistic, which new structures need to be developed, who and where the ecological stewards are, and what types of investments may result in systems change. Finally, we conclude with a discussion of implications for future empirical research and practice, with a call to action for individuals and institutions.

Leveraging an ecosystems perspective for STEM mentoring

The ecosystems framework originated within biological research, which has examined organisms within habitats, with living and nonliving elements, as a complex, dynamic context (Loreau, 2010). Rather than trying to understand an organism's thriving in isolation, an ecosystem analysis helps place the organism in context, zooming out to the system level to consider the elements needed within that context for the organism to thrive. Bronfenbrenner's (1979) work extended this system to human development, illustrating the contributions of an array of *microsystems*, or those most directly encountered in daily development. The microsystems provide individuals with access to certain support resources, such as mentors, which can include extended family networks from the home and faculty or advisors from school.

Mesosystems refer to interactions or interdependency among microsystems, such as how supports or messages from home and school amplify or reinforce one another, or conflict. *Exosystems* refer to features of the system that serve to indirectly influence development, such as the community networks available to the home or those which populate school boards, and the funding available for schools and communities to support development. The *macrosystem* level refers to the broader values and movements at large that inform the availability of community networking to include political and economic changes, as well as historical challenges contributing to which groups are minoritized within particular fields of study. Within the STEM context, we can see how immigration policies (Hira, 2010) and federal funding guidelines for broadening participation (Holloman et al., 2018, April), for instance, reflect historical shifts and policy changes, which have subsequently shaped access to higher education and career attainment in STEM.

Those taking an ecosystems perspective often engage in ecological asset mapping, which involves identifying and creating an inventory of the assets and gaps in the system. For example, researchers interested in wellness may enlist community members to walk their neighborhoods to map valuable spaces and resources such as parks and grocery stores (Santilli, Caroll-Scott, Wong, & Ickovics, 2011). Asset mapping reflects a collective form of taking stock; it is a process that may begin with an analysis of individual attributes within the particular context and then shift to an analysis of challenges in the aggregate (Borrero & Yeh, 2016). Ecological mapping can also be referred to as conducting an environmental scan; this may entail interviewing key stakeholders or analyzing reference documents, in order to inventory community assets and vulnerabilities, before any new structures are proposed (Sibbald, McPherson, & Kothari, 2013). An ecosystems perspective, then, encourages stakeholders to look past the individual level in order to appreciate a system's resources and gaps, which may contextualize challenges individuals face (Flynn, Sanchez, & Harper, 2011).

A STEM Mentoring Ecosystems framework

We offer a STEM Mentoring Ecosystems (STEM-ME) framework to better situate, understand, and push on the mentoring systems that are needed to bring about change in STEM fields. We see benefit in taking lessons from the asset and vulnerability mapping strategy undertaken in other fields and applying the approach to the work of STEM mentoring. A STEM-ME perspective encourages zooming out to the system level to understand what is affording some sources of mentoring or recipients of mentoring to be lifted up or depressed; why certain capacities of mentoring are consistently cultivated or absent; which patterns of mentoring interactions are more or less productive; and the structural components that effectively serve to cultivate connections among mentoring microsystems, larger systems, and/or policies.

To create the STEM-ME framework, we sought to understand the connections between the many ways in which mentoring occurs, existing types of mentoring structures, and the interactions that contribute to the development of mentoring ecosystems. In higher education, mentoring occurs in various ways: student-student, faculty-student, faculty-faculty, in program cohorts, and by program administrators. First, we analyzed the current situation of mentoring related to a specific group of people, in this case, minoritized or historically-excluded individuals in STEM. In seeking to understand the characteristics of these ecosystems, we wanted to address how the STEM mentoring ecosystem is structured and, consequently, who the infrastructure serves. Once these systems were mapped out, we had a better understanding of the overall landscape. Next, we wanted to understand what people bring to their ecosystems and how they interact with and navigate through these systems. This led us to examine and discuss the individual nature and interactions of people to postulate what assets they bring, what vulnerabilities they encounter, and what outcomes

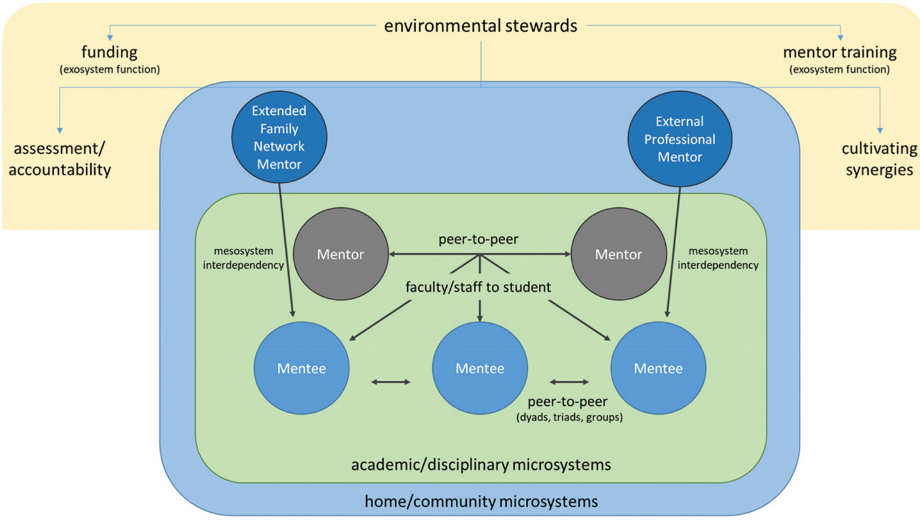

Figure 1. Cultivating Synergies in STEM Mentoring Ecosystems.

subsequently develop within the system. This approach helped us to better understand the mentoring environment and how it could change. Throughout the process, we repeatedly used the aforementioned steps to methodically analyze and understand the systems.

From this process, we identified several stakeholders and systems that cultivate synergies in STEM mentoring ecosystems: mentees, mentors, and environmental stewards who traverse academic/disciplinary and home/community microsystems, see Figure 1.

In the STEM-ME framework, mentees and mentors may experience mentoring as peer-to-peer and/or faculty/staff relationships. These relationships occur within academic/disciplinary microsystems. In addition, mentees may also be mentored by extended family or external professional mentors. These mentoring relationships occur with home/community microsystems which encompass academic/disciplinary microsystems. Lastly, environmental stewards negotiate resources (e.g., funding, training) and should shoulder accountability for assessing and cultivating synergies within microsystems. From this understanding, we use a STEM-ME framework to critique mentoring infrastructures, training, resources, silos and opportunities for developing new structures and identifying stewards and needed investments. In the following section, we use the STEM-ME framework to better understand the assets and gaps of the existing STEM mentoring ecosystems.

Existing STEM mentoring ecosystems that support student success

An asset mapping of the current STEM ecology does reveal many strengths. Although there may not be specific institutional offices or point persons charged with STEM mentoring, there most certainly are associated entities. Most campuses have offices dedicated to faculty advancement, teaching excellence, and research and grants procurement; they also typically have a science or math learning center, an undergraduate research office, and centers for women or minoritized students in engineering or sciences. Many campuses have recognized scholars and/or master practitioners who have reputations for excellent mentoring or advancing students in STEM and/or other fields of study across academic affairs, student affairs, and the university level. Next, we analyze existing STEM mentoring ecosystems by focusing on the undergraduate and graduate student mentoring by faculty and staff, before turning to the infrastructure supporting students and administrators as mentors.

Faculty and staff mentoring of undergraduate and graduate students

Inherently, faculty are entrusted with mentoring students for careers in the STEM workforce. Mentoring undergraduate and graduate students is essentially on-the-job training for faculty members; they identify the approaches and coping strategies (Carver, Scheier, & Weintraub, 1989) that work for them as they engage with their students (Mondisa, 2018; Mondisa & Adams, 2020), even if these approaches are not empirically-grounded mentoring practices. Consequently, most faculty mentors' work is experimental at best, at the expense of mentees (Campbell, 2007).

While mentoring occurs in both formal and informal capacities (Pfund et al., 2016; Ragins & Kram, 2007), for the past two decades, research has focused on formal relationships, typically as part of a recognized program or intervention. Many STEM departments organize formalized mentoring programs for students, with the intention that mentors will provide structured support to students, often in concert with gaining research experience; many of these programs are funded by grants or endowments. While those with strong name recognition include the Meyerhoff Scholars program (at University of Maryland, Baltimore County), the STEM Posse program, and the National Institutes of Health's MARC program, it is rare to find an institution without at least one program operating.

Undergraduate mentoring often occurs in dyads or, even more frequently in large laboratory settings, in triads involving a senior researcher, one postgraduate mentor, and the mentee (Aikens et al., 2016; Packard et al., 2014). On many campuses, the undergraduate research office provides mentor training. Recent analyses indicate that newer STEM graduate students are recipients of cascading mentoring from senior graduate students or postdoctoral scientists, with successful outcomes (Feldon et al., 2019). Some graduate mentoring programs are supported by grant initiatives such as the NSF Alliances for Graduate Education and the Professoriate program (O'Meara et al., 2019). On some campuses, the graduate school may oversee, coordinate, or partner with multiple mentoring initiatives and they may sponsor training or lend other support (e.g., evaluative, support staffing). Beyond their faculty advisors, graduate students may have access to mentoring from their thesis committees. Some college campuses dedicate support to the mentoring of students as a community, especially those from historically underrepresented populations. For example, Historically Black Colleges and Universities (HBCUs) and Minority Serving Institutions (MSIs) have initiatives and long-standing cultures that support the academic achievement of students through mentoring (Hurtado, González, & Galdeano, 2015; Palmer, Davis, & Thompson, 2010).

The STEM mentoring ecosystem may serve undergraduate and graduate students well if they have advocates who steer them into effective, formal mentoring programs. If students are strong advocates for themselves, they may seek out mentoring informally (Montgomery, 2017; Ragins & Kram, 2007). In some cases, informal mentoring is also effectively facilitated by a third party (Hernandez et al., 2017).

Limitations of efforts to provide mentoring to students

As formalized programs often have access to staffing, training, and evaluation support, these tend to be the places where much of the mentoring takes place. Consequently, those not involved in formalized programs may be overlooked, while informal mentors may miss out on support and acknowledgment for their mentoring contributions. Research suggests that perceptions of the effectiveness of mentoring, particularly from faculty or committees, may vary widely on both sides of the relationship equation, as dysfunction and betrayal may occur (Lechuga, 2011; Patton, 2009). Further, organizational barriers may contribute to a 'mentoring tax' such that racial minorities require more navigation (across, within, and outside of organizations) in order to find mentors with similar demographics (Blake-Beard, Murrell, & Thomas, 2007, pg. 12). In addition, Milkman, Modupe, and Chugh's (2015) study demonstrated that faculty, regardless of their own race and gender, were more apt to reply to requests for mentoring from White male students. Thus, the culture has not necessarily changed even as more mentoring programs have become increasingly available.

Another critique of program-based interventions is that they focus primarily on individuals and traditionally prioritize 'fixing' the individual to promote success. In doing so, the programs can be deficit-based, rather than based on mentoring which engages 'critical consciousness' and addresses systemic issues related to equity (Weiston-Serdan, 2017, p. 1). Deficit-based interventions largely target improving individual performance relative to institutional demands or cultural norms, reflecting mentoring approaches that are engaged through an assimilatory lens (e.g., Paris, 2019). In other words, traditional mentoring programs seek to support students to be successful within a system that is viewed as static or infallible.

In addition, a program-based approach to mentoring can be intensive and exclusive, as programs often serve only a small number of students (Packard, 2015). Their expense in terms of time and cost can impede scaling, and exclude those who would be otherwise interested in participating. Thus, additional mentoring needs to occur outside of programs in order to reach a wider array of students and mentors. For informal mentoring to occur, students may have to rely on their own advocacy skills to seek and secure access. However, students may seek out mentors from similar demographic backgrounds; the lack of ability to find such individuals is underscored when describing the isolation of minoritized individuals in STEM (Crisp, Baker, Griffin, Lunsford, & Pifer, 2017; Griffin, 2013; Madyun, Williams, McGee, & Milner, 2013). Research has documented that a lack of similar demographics may still result in positive outcomes (Blake-Beard, Bayne, Crosby, & Muller, 2011), particularly when mentors and mentees have shared values (Hernandez, Estrada, Woodcock, & Schultz, 2016). Yet, more is needed to understand how to overcome this barrier within informal mentoring in a system that has minoritized particular groups.

National infrastructure to access mentors and preparation for effective mentoring

Individuals and institutions alike may access mentoring training and training resources outside of their institutions. In this section, we examine the availability of online platforms through external, technology-supported platforms. We also consider the assets of professional or disciplinary organizations and societies.

Technology-supported mentoring

The availability of technology-supported mentoring resources has grown in the last two decades (e.g., Gosha, Billionniere, Gilbert, & Ramsey, 2010; Packard, 2003). From a practical standpoint, given the predominantly White and male demographics of faculty at many predominantly White institutions, technology-enabled solutions provide a greater variety of racially- and gender-diverse mentors in academic, business, and interpersonal realms. Mentoring is constrained if it only takes place face-to-face and with participants within a certain geographic proximity. Technology-supported solutions help expand the range of mentors available to mentees.

MentorNet, a 501(c)(3) virtual mentoring organization, has contributed to the mentoring of women and underrepresented racial groups by leveraging STEM industry mentors at a distance. MentorNet notably provides research-informed training to both mentors and students, enhancing efficacy of the initiative

(Blake-Beard et al., 2011; Kasprisin, Boyle Single, Single, & Muller, 2003; Kasprisin, Single, Single, Ferrie, & Muller, 2008). In a similar spirit, many colleges and universities are developing alumni distance mentoring programs, using email or videoconference to expand mentoring opportunities for students.

Beyond formalized programs, social media platforms are being used to make formal or informal connections with peer or senior mentors (Montgomery, 2018c) or to tap into professional development (Gosha et al., 2010). Others are developing chatbot technology to simulate conversations with experts, as a potentially scalable and sustainable source of mentoring (Mack, Cummings, Huff, Gosha, & Gilbert, 2019). This is an area we anticipate will only continue to grow to meet the needs of a diversifying workforce.

National-level resources promoting the study and training of mentors

Admittedly, few national mentoring centers and networks exist, but their arrival in the ecosystem is welcome for what they provide. Two national mentoring resources that have increased availability to mentor training for some faculty and staff are the Center for the Improvement of Mentored Experiences in Research (CIMER) and the National Research Mentoring Network (NRMN). CIMER is a nationally-recognized center at the University of Wisconsin (UW), Madison that focuses on the development, implementation, evaluation, and dissemination of mentor and mentee training and resources; they produced the *Entering Mentoring* and *Entering Research* curricula, which provide mentoring case studies and scenarios. NRMN operates similarly, with opportunities within a consortium for individuals at various levels. Collaboratively, CIMER supports the development and provision of mentoring resources while NRMN coordinates mentoring networks and resources.

Professional or disciplinary organizations and societies

Most historically minoritized groups have professional and disciplinary organizations and conference venues that offer different aspects of mentoring resources for undergraduate students, graduate students, and senior professionals alike. One example is the Society for Advancement of Chicanos/Hispanics and Native Americans in Science (SACNAS). In addition, the organization has a mentoring program that convenes mentors and mentees at an annual conference, as well as a *conversation with a scientist* mentoring event (see https://www.2019sacnas.org/mentor/). The conference serves as a destination for institutions seeking to connect with underrepresented scientists for recruiting and learning more about effective mentoring practices.

Another example is the National Society of Black Engineers (NSBE). Similar to SACNAS, NSBE offers an annual convention and chapter membership, which facilitates community building. NSBE also has special interest groups, leadership institutes, and a robust corporate partner infrastructure, providing resources to help institutions better understand how they can play a role in increasing the number of Black and African American engineers in the field, such as through a professional development mentoring program (https://my.nsbe.org/participate/mentoring). Within engineering, other affinity-group professional societies exist, including the Society for Hispanic Professional Engineers and the Society of Women Engineers.

Beyond formalized organizations, formalized conference venues have gained reputations for their mentoring capacity and service. One example is the Annual Biomedical Research Conference for Minority Students (ABRCMS), a program of the American Society for Microbiology (Hulede, 2018). Hundreds of colleges and universities participate in the conference over a set of days, providing not only presentation experience, but also mentorship to more than 2,000 students from diverse racial and ethnic backgrounds. A similar conference, providing a source of mentoring support to the profession with a focus on women in computer science, is the Grace Hopper Celebration.

Limitations of national-level resources to access and prepare mentors

There is a need for long-term, evidence-based, sustainable mentor training for faculty and staff that is not currently offered via national networks. Existing national networks like CIMER and NRMN provide periodic practice and discussion and great resources and strategies for dissemination, but are not necessarily positioned for the kind of integration into departments and universities that will fundamentally shift the quality of mentoring at scale. Faculty who do receive mentoring training and certification as facilitators of mentoring training sessions from CIMER may be burdened with the responsibility of facilitating mentoring training at their home institutions, while frequently not receiving any incentive or recognition to do so. This is a significant limitation in our current systems.

Additionally, despite numerous and emergent mentoring resources, many faculty still lack explicit information about ways to conduct student-faculty mentoring relationships. Participating in a training event, even one of very high quality, is different than engaging in daily mentoring with students. In the absence of effective systems of implementation, coaching, and accountability, students and faculty mentors may not benefit in practice. Compounded by the limited focus on mentoring undergraduate and graduate students, many institutions are only beginning to grapple with the institutional commitment to effective mentoring for and by postdoctoral scientists.

Mentor training needs to be improved with regard to contextual and cultural competence. Despite awareness of the need for greater cultural competence, one specific area that requires more emphasis is how to effectively talk about and address race, or to engage in difficult conversations about power and privilege, as a core part of mentoring practice (Valantine & Collins, 2015). Mentors may lack the space, time, resourcing, and incentive to gain these competencies. While national organizations, conferences, and other resources exist, it is most likely that faculty seeking out these resources are not the ones who most need to grow their mentoring skills. While the optional community nature of these organizations and spaces contributes to their value, stronger communication pathways to disseminate and embed best practices within the departments of those who partake in these important communities would strengthen the mentoring across departments and universities.

Infrastructure to prepare students for mentoring roles

Within STEM, we need to acknowledge the contributions of students who take on the role of daily peer or near-peer mentors, whether in classrooms, academic support spaces, or labs. At research universities, graduate students often take on this role. At many institutions, seasoned undergraduates are doing the same.

In the classroom, peer mentors support the curriculum with varied terminology and functionality, but ultimately they share a common goal: they invest in and cultivate the strengths of introductory students who are learning key habits of mind and developing their identities in STEM. Whether through peer-led study groups (Barnard et al., 2018), supplemental instruction (Rath, Peterfreund, Xenos, Bayliss, & Carnal, 2007), peer-facilitated workshops (Preszler, 2009), learning assistants (Otero, Pollack, & Finkelstein, 2010), or peer code reviewers (Pon-Barry, Packard, & St. John, 2017), results indicate increased student success when introductory courses have peer mentoring resources in place. Specifically, students who participate in peer mentoring earn higher grades and are more apt to persist to subsequent courses; many peer-based initiatives help address equity gaps in performance (Preszler, 2009; Rath et al., 2007). Peer mentors also grow and develop a stronger commitment to the field (Bowling, Doyle, Taylor, & Antes, 2015).

Researchers have also examined the preparation of undergraduate and graduate peer mentors for mentoring roles. Pedagogy courses are common, providing technical skills, leadership development, and opportunities to learn about culturally relevant, inclusive practices (Barnard et al., 2018; Gillian-Daniel & Kraemer, 2015; Pon-Barry et al., 2017). In the research domain, undergraduate researchers are encouraged to return in subsequent years and serve as mentors for newer students, a beneficial practice correlated with increased persistence and commitment to the field (Thiry, Weston, Laursen, & Hunter, 2012). Undergraduates may also feel a stronger sense of belonging if mentors reflect demographics similar to their own; despite a lack of faculty diversity, peers can provide important role modeling (Dasgupta, 2011).

Analyzing the available infrastructure, a science learning center may support undergraduate teaching instruction, while a campus teaching center may support graduate student instruction. Often a research office will sponsor research mentoring preparation. Beyond the individual campus, there are a growing number of support programs in place to prepare teaching assistants and resident assistants. Numerous research mentors at the faculty, postdoctoral, and graduate levels have had exposure to the *Entering Mentoring* curriculum generated by the UW team (Handelsman, Pfund, Lauffer, & Pribbenow, 2005), which formalized and made accessible key expectations, ethics, and practices of effective science mentoring. Graduate students who went through this training were noted as paying more attention to diversity, equity, and inclusion (DEI) issues (Pfund, Pribbenow, Branchaw, Lauffer, & Handelsman, 2006). CIMER has also disseminated broadly accessible and tested survey tools developed by a UW Institute for Clinical and Translational Research research group that measure the *Entering Mentoring*competencies of mentors (Fleming et al., 2013; Handelsman et al., 2005; Pfund et al., 2014).

The Center for the Integration of Research, Teaching, and Learning represents a consortium of 37 institutions to leverage graduate education to advance evidence-based teaching practices for diverse learners. As described by Gillian and Kraemer (2015), the investment in professional development of graduate instructors in areas including culturally relevant pedagogy improves not only the competency and self-efficacy of graduate instructors, but also outcomes for historically underrepresented students. Investments in mentoring at the student level provide great hope for cultural change (Hund et al., 2018). Requirements for graduate instructors or fellows, and certainly undergraduates, can be made more easily, as compared to requirements at the tenured faculty level. When graduate and undergraduate students undergo training, they may expect further training in the future (Pfund et al., 2006), which benefits the entire system.

Limitations associated with efforts to prepare students as mentors

While there is an awareness that investing in the preparation of students as mentors is necessary to improve outcomes, this does not mean training efforts are consistent. A challenge in this domain is that the students still require mentoring themselves while developing in their roles as mentors. Not all mentoring toward this end is productive; some is dysfunctional (Ghosh, Dierkes, & Falletta, 2011) and some mentors torment rather than support (Lunsford, 2014). Reports from graduate students, in particular, outline numerous barriers that may contribute to dysfunction (Thomas, Willis, & Davis, 2007) and microaggressions (Gomez, Khurshid, Freitag, & Lachuk, 2011). Undergraduate mentors may feel undermined in their role if not supported adequately (Packard et al., 2014). Student mentors may not always be able to ask for what they need, depending on how culturally sensitive or knowledgeable the supervisor is.

Mentor training provided through CIMER and NRMN is mainly focused on research relationships. Mentoring needs often include socioemotional and psychosocial support for which peer and near-peer mentors may or may not be adequately prepared. Furthermore, much of the training focuses on mentoring in formal programs, whereas many peer interactions may occur informally in study spaces, clubs, and classrooms, where peer exclusion may be taking place. In addition, current systems for supporting student-to-student mentoring at the undergraduate level are often disconnected from those that serve faculty. Although graduate student instructors may be included in workshops from teaching centers, they may not be included in mentor training if they are not the formal mentor of record. The system loses out on possible synergies that may arise from responding to similar challenges.

Infrastructure to develop faculty and administrative leadership

Some institutions have institution-wide faculty mentoring programs that focus on mentor training, education, and resources for faculty. These programs may focus on guiding individuals toward the pursuit of institutionally defined goals such as timely graduation for students and publishing or obtaining grants for faculty (Montgomery, 2018b).

Mentor training and support for faculty and staff may also be supported by external faculty-centered programs (e.g., CIMER, NRMN) and/or resources and grant-sponsored or institutionally based programs (e.g., the NSF ADVANCE and INCLUDES programs, the Big Ten Academic Alliance, institutional DEI programs, and mentoring program mandates). Faculty may participate in peer circle mentoring programs or learning communities, which provide rich opportunities for group and both informal and facilitated peer mentoring (Files, Blair, Mayer, & Ko, 2008; Thomas, Lunsford, & Rodrigues, 2015). Likewise, at the college and institutional levels, programs may offer faculty training and resources about mentoring, such as the NSF's ADVANCE program, which is targeted at promoting the success and advancement of women in STEM.

There are national resources that provide support to faculty and administrative leaders, including the Academic Conference of Academic Deans, the American Council on Education, the Association of American Colleges and Universities, the National Association of Diversity Officers in Higher Education, the National Conference on Race and Ethnicity in Higher Education, and the Council of Independent Colleges, among others. These may be drawn upon to augment offerings at an individual campus.

Limitations associated with infrastructure to mentor faculty leaders and administrators

Current programs may not provide explicit examples of ways to engage in mentoring relationships with students, or an effective means for assessing efficacy. However, most existing faculty mentoring programs focus on mentoring faculty about ways to be successful in their careers; they do not focus on providing specific knowledge or strategies that can be used to improve their mentoring practice (Christe, 2013; Thomas, Bystydzienski, & Desai, 2015). While multiple organizations offer resources to faculty, campuses vary in their funding for these external programs, and may be able to send only a limited number of individuals, limiting the impact of those resources to the campus itself.

An ecosystem approach to mentoring recognizes that while successful mentoring interactions can be initiated and carried out by individuals, mentoring interventions are most effective when ingrained in the unit or larger institutional culture or ecosystem (Montgomery, 2018a, 2018b). For an ecosystem-based mentoring culture to thrive, institution-level systems of accountability and specific individuals responsible for stewardship must be in place. These individuals can serve at the micro-ecosystem level, that is, mentors and collective mentor networks, and at the macro-ecosystem level, that is, leaders who establish and cultivate infrastructure, mentoring cultures, and systems of implementation and accountability.

Cultivating synergies in STEM mentoring ecosystems

Understanding STEM mentoring ecosystems presents opportunities to identify ways to cultivate synergies among existing microsystems. Especially in contexts where generating new resources or funds to grow new systems is not feasible, and even where the capacity to grow or create new interventions is there, we recommend connecting existing infrastructure and resources to make them more synergistic. Additionally, revamping existing resources to be more effective may help to fill gaps; the intended goal is to assist any institution in improving its existing circumstances through intentionally connecting and utilizing existing structures before adding new resources to the system.

Academia relies on specialization and expertise, yet this expertise often exists in silos. Many campuses organize their faculty and staff into disciplinary groups. When academics publish their work, they often do so in specialized journals, and many have their own pedagogical journals (e.g., *Journal of Engineering Education, Journal of Chemical Education*). Without a concerted effort, mentoring lessons learned in one field would not easily be found by someone working in another field.

In a similar vein, many campuses organize advising in a decentralized manner, which is dispersed across offices throughout different colleges. These offices may or may not be in conversation with student success offices, undergraduate research offices, graduate schools, and so on. While there may be centralized teaching and learning at the university level, the scope of this work may or may not intersect with STEM mentoring, whether in research labs or the classroom. Diversity, equity, and inclusion offices may be centralized or decentralized, depending on the campus; while concerned with campus climate issues and anti-bias education, DEI offices may or may not be in conversation about teaching and learning, undergraduate research, or the graduate school. One of the potential dangers of working in silos is that we do not actively integrate our systems, draw intentionally on the interdependency of elements of the STEM-ME, nor actively seek to cultivate synergies in the mentoring realm. While central organization is not necessary to advance a thriving mentoring ecosystem, we acknowledge that the advancement of teaching and learning initiatives as well as research excellence has benefitted, in some cases, from centralized organizational support.

The need for stewardship in STEM mentoring ecosystems

STEM mentoring ecosystems are tended by stewards, who hold responsibility for holistically assessing how mentoring relationships are interconnected and how the environment is either promoting or inhibiting what is happening in these exchanges (Montgomery, 2019b). To serve most effectively, stewards must be individuals with institutional standing, access to resources, and the ability to establish systems of reward and accountability at the highest levels, as well as day-to-day responsibility and authority to ensure implementation. Environmental stewards at the micro-ecosystem level can be peer mentors or mentors functioning in more classically hierarchical pairings, as described in previous sections; yet, where effective stewardship will persist beyond a single individual mentor-mentee pair or larger mentoring network, ultimately stewardship must extend to the leadership level (Montgomery, 2020).

A need for leaders in establishing mentoring cultures has been previously advanced (Whittaker et al., 2015). Even as we recognize the role of individual staff and faculty in leading mentoring work, we also recognize that organizational leaders such as department chairs, deans, and other unit or university leaders play important roles. They may provide financial resources or mentor or anti-bias training, or create and monitor systems of assessment and accountability, including those that guide assessments of how faculty should spend their time. Standards are apparent in measures of annual evaluation and in guidelines related to reward, promotion, and tenure (Whittaker et al., 2015). Leaders have multiple opportunities to support effective mentoring, by serving as mentors themselves and promoting mentoring cultures in the units in which they hold responsibility (Bensimon, Ward, & Sanders, 2000; Bower, 2007; Laden & Hagedorn, 2000; Whittaker et al., 2015).

To establish and maintain a functional mentoring ecosystem, specific investments must be made. We need to ask what resources, accountability, and assessment measures can promote a culture of mentoring that is more effective and consistent than the one in place now at most institutions, and more holistically across STEM fields. To ensure that micro-level mentor pairings (e.g., dyads or triads) are effective, plentiful, and sustained at the macro level (i.e., in the ecosystem) requires intentional, strategic planning and enactment. Institutions generally invest resources and personnel in areas of high priority. For example, nearly all research universities and most colleges have a high-level executive position related to promoting research excellence. Similarly, most campuses have a senior leader with responsibility for teaching and learning centers or foci. Such centers are the universities' lived commitments to areas of high priority in terms of faculty work in academic ecosystems. When campuses prioritize mentoring and hold themselves responsible for ensuring that faculty, staff, students, and administrators are trained and held accountable for effective mentoring, similar commitments, resources, and structures will emerge.

Implications for future work

Effective, functioning STEM mentoring ecosystems provide faculty, students, and administrative leaders with access to training and resources that support their mentoring of undergraduate and graduate students. Healthy, thriving STEM mentoring ecosystems also designate and empower environmental stewards, who assess existing mentoring infrastructures and then recognize interdependencies and cultivate synergies within the systems. To enhance the functions of mentoring ecosystems, we ask what synergies could be created within our particular environments before asking which new investments are needed to advance this work. We invite others to consider the following implications of a mentoring ecosystems framework to analyze their systems and make visible the necessary mentoring structures and advocates.

Implication 1: a framework to analyze mentoring ecosystems in research and practice

The implications for future empirical research are manifold. For example, future researchers can use the STEM-ME framework to assess various mentoring contexts (e.g., programs, relationships, etc.), to study the capacity for quality mentoring, including what supports mentors are being provided to grow their mentoring. Empirical research could also analyze different organizational solutions (e.g., the addition of a STEM mentoring office) or policies (e.g., changes to promotion and tenure guidelines to include mentoring quality). Subsequently, in using this conceptual framework, future researchers may strengthen the rigor and variety of empirical mentoring studies.

We propose a STEM-ME framework to be used as a practical guide to help students, faculty, and administrators better understand the characteristics and functions of mentoring ecosystems. Specifically, the following questions, which we used to analyze current infrastructures, can be used by institutions in their assessment: (1) What is the current state of the mentoring ecosystem? (2) How is the ecosystem set up? (3) Who does the ecosystem serve? (4) How are people functioning in the ecosystem (what are their assets and outcomes; what are their gaps or limits)? and (5) How are people intentionally integrated in the ecosystem or leveraging synergies? We recommend that faculty and administrators can use the STEM-ME framework in beginning to understand and assess mentoring ecosystems at their institutions prior to developing or implementing changes.

Implication 2: need to cultivate stewards who work synergistically

To optimize mentoring ecosystems, institutions must invest in stewards who can empower others and identify, enhance, and leverage existing resources and create new synergies. A comprehensive environmental scan will likely uncover a wealth of resources already in place – for example, programs with robust mentoring components, local individual mentoring champions, and relevant training resources – that can be leveraged for greater outcomes simply by thoughtful planning and implementation of dissemination and connection strategies. For such leveraging to work well, a structure of support and accountability needs to be established which includes environmental sensors and environmental stewards. In addition to boosting awareness and facilitating connections, there is often a need to cultivate synergies and ways to support continual improvement, before making any costly investments for entirely new initiatives. We anticipate stewardship of mentoring ecosystems to inform future research agendas as a way to make sense of effective mentoring at the system level. Further, an examination of stewardship is a useful practical recommendation for institutions to undertake to promote mentoring sustainability.

Implication 3: need for culturally relevant/sustainable mentoring approaches

Across all levels, mentors need to utilize culturally relevant approaches. Mentors need to identify and implement context-specific approaches. Such approaches take into account the environmental context of mentoring (the representation of certain groups, or lack thereof, within environments); histories of inclusion and exclusion; and uses of this knowledge to inform specific mentoring practices and interventions (Montgomery & Page, 2018). Mentors need also to consider the framing of messages given the social contexts, such as when providing difficult feedback on performance (Montgomery, 2019a; Packard, 2015). Likewise, mentors' cultural competence can be crucial with mentees from minoritized groups (Mondisa, 2020). Accessing and leveraging mentoring knowledge through inter-institutional partnerships with HBCUs and MSIs can help enhance diversity (Whittaker & Montgomery, 2012). Mentoring that integrates culturally relevant approaches and considers context can lead to mentoring as a form of environmental stewardship (Montgomery, 2019b). Future research and practice will need to better understand how mentors aim to demonstrate their cultural responsiveness and where and how mentees look for this evidence in practice.

Implication 4: a need to understand mentoring experiences of minoritized populations

Understanding the needs for access, equity, and mentoring from the critical views of minoritized populations is greatly needed in research (National Academies of Sciences, Engineering, and Medicine, 2019). Future researchers should examine how mentoring ecosystems influence the mentoring experiences and issues of inequities and access to mentoring of minoritized populations in STEM. Improving the system will require disruption. Sometimes, only disruption allows new approaches to come in and be embedded in the system. By understanding the mentoring needs of minoritized groups, and centering rather than marginalizing those needs, we can help improve mentoring ecosystems that are essential to supporting students' matriculation and success. In examining this, future research can provide a holistic perspective of how mentors, mentees, and environmental stewards can address improving mentoring for minoritized populations within ecosystems.

A call to action for individuals and institutions

We propose that the academy must recognize existing mentoring resources at individual and institutional levels *and* invest in the leveraging of these resources to create synergies and support the development of environmental stewards of STEM mentoring ecosystems. Mentoring must be legitimized as a core, shared responsibility of both individuals and institutions, and institutions and leaders may need to disrupt systems to facilitate progress in this realm. Such disruption may be necessary to truly change the experiences of mentoring for minoritized groups in STEM. As faculty and administrators, we can all be stewards in our own smaller ecosystems and this requires pushing back on resistance to change. By using the STEM-ME framework, institutions can demonstrate a willingness to leverage existing resources and take steps toward understanding the states, vulnerabilities, and infrastructures of our ecosystems. By determining who has the systems purview in our institutions, we can address areas identified as having the need for the development of new resources and where opportunities exist to designate stewards and create synergies of existing resources to support mentoring ecosystems. Using a collective effort, we can capitalize on existing resources to create synergies across mentoring ecosystems that will assist in eliminating mentoring silos and supporting the academic success and professional development of respective stakeholders.

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