Snapshot of an interdisciplinary graduate engineering education experience

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Introduction

The necessity of interdisciplinary collaborations to address future problems is prominent within engineering fields in efforts to address the grand challenges of engineering within the 21st century[1]. To target the interdisciplinary skills required of engineers to address these future problems, various education reform efforts have been established at all levels of the education continuum including K-12[2], undergraduate[3] and graduate education[4]. Although much is now known about effective learning environments, there is a need to focus on the translation of this research to practice[5–7]. Lemke[8] in 1997 urged that "[i]t is time we made an effort to investigate our practices closely with the aim to innovate," strongly criticizing the engineering education research community for not practicing what they preach. In recent discussions of this concern, it has been identified that "…the issue is not simply a need for more educational innovations. The issue is a need for more educational innovations that have a significant impact on student learning and performance, whether it is through widespread and efficient implementation of proven practices or scholarly advancements in ideas, methods, or technologies (p. 5).[6] " Efforts towards this end have included the development of frameworks and strategies to make the link between knowledge generated in the learning sciences to the practical delivery of education more explicit and implementable[5,9,10].

In particular, graduate education has identified interdisciplinary skills as an essential component of tertiary training[11,12] and one prominent interdisciplinary program that has been established in the United States to this end is the NSF supported Integrative Graduate Education and Research Traineeship (IGERT) program[4]. IGERT recognizes the need for renewal of graduate education to reflect the increasingly more interdisciplinary context of research and education and provides five years of funding per program to "catalyze a cultural change in graduate education, for students, faculty, and institutions"[4]. Resulting IGERT programs at different institutions have attempted to address the challenge of interdisciplinary research training and education programming in a variety of ways including the collaboration of different technical and non-technical traditional disciplines, (for example, partnering engineering Ph.D. students with MBA and law students[13]), exposure to global experiences such as international internships[14], and reframing approaches to the development of graduate curricula and interdisciplinary teams[15,16].

The purpose of this study is to provide a snapshot of an IGERT initiative, IGERT in Magnetic and Nanostructured Materials (IGERT-MNM), which deviates from the norm and has accommodated aspects of design-based research methods[17] (DBRM) in the design, implementation, and continual improvement of a novel interdisciplinary training program. IGERT-MNM researchers, practitioners, and learners contribute to the iterative re-design of the activities within the context of three different university settings. The results of this study show that graduate students may function as valuable collaborators to learning scientists and education practitioners in the design of interdisciplinary learning environments that will prepare professionals ready to meet yet unforeseen challenges.

Background

Interdisciplinary education is relevant in the area of "convergent technologies" as exemplified by the "synergistic combination of four major 'NBIC' (Nano-Bio-Info-Cogno) provinces of science and technology, each of which is currently progressing at a rapid rate (p. 282)[18]".The explosive growth of knowledge, techniques, and applications derived from research in nanoscale science and engineering, and the increasing necessity of integrating disciplines to address complex problems require non-traditional approaches to prepare young researchers. Graduate programs readily offer in-depth, textbook-based instruction on tested-and-tried content, but no formal training on the process of developing the content. Students are expected to learn how to ask good research questions, build on the work of others, formulate an effective and feasible research design, and analyze and synthesize results. However, these essential outcomes of graduate education seem to happen more as a by-product than an intentional result of formal mechanisms. Beyond mastering knowledge and the process to produce it, students must also acquire a myriad of professional skills and information to succeed in their desired career paths. The IGERT-MNM Education and Training program addresses these three missing elements in graduate education by (1) offering instruction on emerging interdisciplinary knowledge, (2) providing formal training to prepare students to become independent researchers, and (3) emphasizing pedagogical and professional development training. In addressing these areas, disciplinary boundaries and traditional graduate education paradigms are challenged through the active engagement of graduate students.

Literature on IGERT programs show that the most popular learning experiences are additional coursework and seminars[19]. These can range from requiring the enrollment in already established university courses outside of the home discipline, new interdisciplinary courses and seminars designed by IGERT faculty, and IGERT students team-teaching undergraduate courses[20,21]. Additional components of various IGERT programs include dual advisory structures for Ph.D. students[21], international visits and internships[14,20,22], and interdisciplinary research teams addressing topical problems presented by experts outside of their home disciplines[20].

With an emphasis on the active engagement and leadership of its graduate students, IGERT-MNM's primary features include participation in and the development of modular courses, research meetings, retreats, conference attendance, outreach activities, international experiences, program management (e.g. committees) and assessment strategies. While at the onset of IGERT-MNM in Fall 2010, the PI was unaware of the most related literature, built into the proposal and execution of the program were characteristics of design-based research[23] such as:

- Being situated in a real educational context
- Focusing on the design and testing of a significant intervention
- Using mixed methods
- Involving multiple iterations
- Involving a collaborative partnership between researchers and practitioners
- Evolution of design principles (p. 16 – 17)[23]

IGERT programs should strive beyond additional coursework and seminars and this funding model provides an excellent opportunity for cyclical evaluation and re-design, along the lines of the design-based research methodology (DBRM)[17]. DBRM can be applied in this context to create a framework for the cyclical design, enactment, and study of an education innovation in a realistic setting.

IGERT-MNM program overview

IGERT-MNM combines the materials science and engineering education expertise at three universities, Norfolk State University, Cornell University, and Purdue University, to create a framework for students to build their own interdisciplinary training experiences. The program seeks to address missing elements in traditional graduate education by providing opportunities for students to (1) acquire knowledge and perform research in emerging interdisciplinary fields, (2) lead integrated research and education activities, and (3) acquire and practice pedagogical and professional skills.

The technical context of the IGERT-MNM program was proposed to broadly expand the design, preparation and characterization of nanostructures that derive their functionality from their compositions, sizes, multi-layered structure, and interfacial and surface properties, with the goal of developing new materials for an important set of high-technologies in electronics, communications, information storage, and medical applications. Engineering education research makes up an equal component in the students' experiences, and is integrated in the context of the students' research interests. IGERT-MNM therefore sustains a multi-campus student and faculty community with members from chemistry, physics, engineering, biology and engineering education communities.

The design of IGERT-MNM is guided by the 2008 report, *The Formation of Scholars: Rethinking Doctoral Education for the Twenty-First Century*, a five-year study sponsored by the Carnegie Foundation for the Advancement of Teaching[24]. The report identifies and provides recommendations to address several long standing challenges to American doctoral education: high attrition, particularly among women and ethnic minorities, long time for completion of degree, and lack of connectedness of academic requirements and opportunities with professional demands[25–27]. Recommendations to address these problems and others also appeared in the earlier 1995 COSEUP (Committee on Science, Engineering, and Public Policy) report, *Reshaping the Graduate Education of Scientists and Engineers*[28]. These recommendations have also informed the design of IGERT-MNM: (1) produce versatile graduates, by providing in depth education in one field, and exposure to related ones, (2) equip students with a variety of career skills for academic and nonacademic professions, (3) form scholars through a student-centered program framework, (4) attract and retain minorities by understanding and accommodating the multidimensional challenges inherent in diversity[5,29] (5) make explicit the different career pathways and assist students as they design their own education[24], (6) offer excellent research training, and (7) be acutely aware of institutional strengthens and interests[30].

Guided by these reports, related literature[31,32], and the goals of the NSF-IGERT program the following **education and training objectives** are sought:

1) To provide IGERT Trainees with an interdisciplinary and collaborative learning and research environment, within a community of scholars, which fosters their understanding of the scholarship of their research areas, and the scholarship of teaching and learning;
2) To develop and offer modular, interdisciplinary coursework that is nimble, responsive to the increasing need to train students from diverse education backgrounds in emerging fields and interdisciplinary content, and to provide guidance for professional skills development;
3) To offer a rich and diverse education and training environment uniquely enabled by IGERT-MNM through the leveraging of resources and expertise in the participant institutions, and opportunities for research at a partner institution;
4) To offer structured programming to encourage teamwork, leadership, and development of management and communication skills that will prepare Trainees to become agents of change, ready to promote renovation of education and research, and address the challenges of keeping America's preeminence in the high-technologies market place;
5) To increase the diversity of persons holding doctoral degrees in the research areas addressed by IGERT-MNM, and revitalize and renovate the science and engineering graduate curricula at Norfolk State University, therefore enhancing the education of a large number of African-American science and engineering students.

Modular courses

Modular courses from the bases for delivery of the programmatic activities and involve faculty and students interacting weekly, throughout the academic year, using videoconference, and other technology-enabled communication means. In addition, during intense, annual multi-day retreats at Cornell University (winter) and Norfolk State University (summer), trainees come together for further technical training, professional development, program self-reflection and redesign.

Most of the education and training part of the program is delivered in four courses: (1) Technical and Professional Writing (6 weeks); (2) Training in Independent Research (12 weeks); (3) Best Practices in Teaching and Learning (8 weeks); and (4) Ethics and Intellectual Property (4 weeks). The sequence of short, focused modular courses provides a framework conducive to the cycle of (re-)design, enactment, and study of the proposed graduate training activities. It allows for students to learn and practice in the same environment, a requirement for situated learning and transfer[9]. Moreover, trainees participate in the modules as students, teachers, and evaluators throughout the course of the program. To this end, trainees at different stages of their graduate studies and different competencies work individually, in teams, and as a whole group; sometimes supported, sometimes unsupported by faculty. As they function in these many roles and interact in different capacities, they develop and exercise the skills to perform the complex activities needed in their future professions, as well as their identities as members of a professional community.

The following was initially proposed for the annual cycle of modular course revision:

Year 1: The IGERT faculty team will develop the modular courses

Year 2: Based on faculties' and students' assessment results, and feedback from the external evaluators and advisory committee, the Y2 Trainees will assist faculty in the improvement and teaching of the modules.

Year 3: Y3 Trainees will prepare and deliver a new teaching module, working in teams, under the supervision of faculty.

Years 4 and 5: Faculty and Trainees will fine-tune modules, and submit them for integration in the regular course offerings at one of the partner institutions.

Changes in the order of course delivery occurred as an important outcome of the integrated assessment of the programmatic activities. Extensive evaluation and redesign has revealed that the integration of the modules makes each of them more effective by facilitating the development of a more meaningful deliverable. Also, seeking to better integrate the activities throughout the modules has led to changes in their order every year, as seen in Table 1.Please note that *each cell at the top of table corresponds to 2 weeks.*

Table 1. Timetable of course delivery each year

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<tr><td>Y1</td><td colspan="3">Writing</td><td colspan="5">Independent Research</td><td colspan="4">Teaching and Learning</td><td colspan="2">Ethics</td></tr>
<tr><td>Y2</td><td colspan="2">Ethics</td><td colspan="3">Writing</td><td colspan="5">Independent Research</td><td colspan="4">Teaching and Learning</td></tr>
<tr><td>Y3</td><td colspan="5">Independent Research</td><td colspan="3">Writing</td><td colspan="4">Teaching and Learning</td><td colspan="2">Ethics</td></tr>
<tr><td>Y4</td><td colspan="5">Independent Research</td><td colspan="2">Ethics</td><td colspan="4">Teaching and Learning</td><td colspan="3">Writing</td></tr>
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The modular courses (modules) have undergone extensive changes based on formal and informal yearly assessment. Following is a summary of the modules as initially proposed.

The <u>Writing</u> module, initially proposed as Professional Communication, aims to provide trainees with the opportunity to learn about the structure and content of diverse documents, and the opportunity to apply this knowledge to prepare documents for technical and non-technical audiences. Trainees were expected to reflect on their development through keeping up an online blog.

The <u>Training in Independent Research</u> module provides a framework to acquaint students with research in IGERT-MNM's interdisciplinary content areas, and to expose them to the processes researchers use to plan scientific investigations. The challenge of preparing research proposals marks the transition from the dependent to the independent stage in graduate students' education. This transition is critical and prompts the development of a set of new skills and behaviors necessary for the successful completion of the doctoral degree and future professional career. This module offers instructional scaffolding to promote students' mastery of the skills and thinking patterns associated with the creative process in science and engineering research.

While the Independent Research module focuses on scientific preparedness, the Best Practices in Teaching and Learning module offers the trainees a window into how they, and others, learn, and how research can guide the design of teaching and learning environments. This module provides trainees scaffolding for the annual redesign and assessment of the IGERT curriculum. Trainees read and discuss relevant literature, guided by an engineering education professor and trainees under her mentorship. The application of educational frameworks such as Backwards Design[33] and How People Learn[5] are used to help guide trainees consideration of how to communicate their personal research to a variety of audiences in a variety of settings for e.g. workshop curricula for high school students and short videos for general audiences. This module also serves as an opportunity for trainees to reflect on their personal research and consider how to select and frame particular content in different situations and purposes—a valuable professional skill in their future careers

The fourth module, on Ethics and Intellectual Property, aims to give trainees a working understanding of standard ethical rules in the discovery environment, and to familiarize themselves with skills and resources needed to identify and address ethical conflicts.

In this paper, we intend to show how the application of DBRM to the writing module in the IGERT-MNM initiative led to its evolution through the first three years. Writing is a fundamental and integrative skill, and the module and the skills learned *within the module*, continue to play a central role as students progress through the other modules.

Writing module evolution from year 1 to year 3

Year 1 (Fall)

Deliverables and outcomes: Trainees will prepare and disseminate information about their research to the general public, differentiate the goals and processes of writing different types of documents, communicate effectively to diverse audiences, and identify resources for continued improvement.

Activities: Two IGERT-MNM faculty members led this module using the text *How to Write and Publish a Scientific Paper* by Day and Gastel[34]. Activities included trainee-led seminars, self-evaluation of writing skills, writing a description of trainee research for broad audiences (e.g. short statement on a website), and evaluating writing effectiveness of journal articles.

Evaluation and Redesign: Informal evaluation was obtained at meetings during the winter and summer retreats. Trainees decided that the module should prepare them to write other kinds of professional documents including cover letters and resumes. Discussions between faculty and trainees also led to the decision to use the writing module as a framework for students to develop an independent, interdisciplinary proposal. The research idea would be further developed and evaluated by the group through presentations to take place during the subsequent Independent Research module. To provide time for trainees to review the scientific literature over the winter break prior to the deciding on a research topic, the Ethics module was moved to the beginning of the fall. The Y2 writing module syllabus was prepared by a team of trainees over the summer, based on their newly acquired knowledge from that year's Teaching and Learning module.

Year 2 (Fall)

Deliverables and outcomes: Trainees will write a short technical document from outline to draft, evaluate their peers' technical writing and provide constructive criticism, and prepare documents for use in future job applications,

Activities: An experienced scientist led a writing seminar on fundamentals of writing a scientific paper. Writing mechanics were targeted through reading and writing activities throughout the module. Additional exercises targeted outlining and describing technical processes (as related to proposal writing). Deliverables included resumes and cover letters for specific job postings that were reviewed and critiqued by peers.

Evaluation and Redesign: Formal evaluation was conducted through an anonymous survey designed and administered by trainees. The ten item survey collected information about satisfaction with activities, presenters, and writing skill improvement due to module participation using rating scales and open-ended responses. In general, trainees felt the module was adequately organized and provided valuable skill development but with room for improvement. Trainees desired a more explicit integration of this module with the Independent Research Module with a focus on research-based writing such as a research proposal, as opposed to other professional documents such as cover letters and resumes. Informal evaluation was again obtained during meetings at project retreats where survey results were found accurate and peer-review of materials was identified as the most helpful component of the module.

The decision was made to move the Independent Research module ahead of the Writing module. That would allow for trainees to develop their research ideas during the Independent Research module in the Fall, and write a white paper as their Writing module deliverable. Faculty suggested a white paper as a more appropriate deliverable than a full research proposal for time and experience considerations. A tricky balance to maintain is ensuring that the modules have enough content to challenge trainees while not becoming as demanding as required coursework and research responsibilities. Again trainees developed the syllabus, which was refined to align with the Independent Research module's objectives and deliverables using information gained from the Teaching and Learning module. The topic of magnetic multilayer materials, which formed the basis for the trainees' proposal development, was found to be far too limiting. The topic planned for Year 3, materials for nanobiotechnology, an inherently interdisciplinary area, was suggested by the faculty and favorably viewed by the trainees.

Year 3 (Fall/Spring)

Deliverables and outcomes: Trainees will prepare an abstract and a summary of the research idea developed during the independent research module, recognize the various types of grants, proposals and funding sources, and develop a white paper from outline to final draft.

Activities: Trainees draft a summary of proposed research to faculty for feedback, develop a 2-minute elevator speech, and attend seminars on writing proposals delivered by IGERT-MNM faculty and a Department of Defense program officer. Feedback methods include group evaluation of peers' draft white papers, individual reflection as well as group reflection and discussion about what has been learned, and faculty evaluation and scoring of final white papers.

Evaluation and Redesign: Formal evaluation was conducted through a revised, anonymous survey designed and administered by trainees. Thirteen items in the survey collected information about trainees' opinions and self-assessment related to activities using Likert scale responses. Five items requested open responses about the value of the module and suggestions for improvement. In general, trainees thought the module was well organized, supplemental resources were adequate, and their general understanding of effective writing had improved. Twelve out of fourteen trainees agreed that the module would be helpful to any graduate student. As shown in Figure 1, the trainees identified improvement in their white paper drafts over the course of the module.

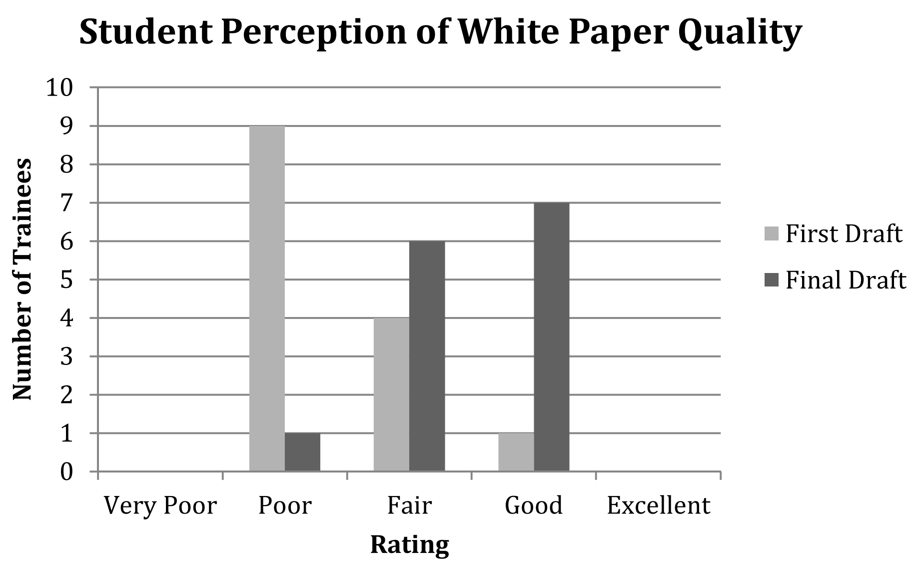

Figure 1. Trainee responses to the survey question – "In general, what was the quality of the first/final draft of your white paper?"

One of the module deliverables was an individual reflection based on the trainee's experience writing the write paper. Although the Figure 1 responses are self-assessments, when asked to provide suggestions for future modules based on these reflections, comments from trainees suggest that a greater awareness of the complexities of developing a sound white paper were gained:

> "I would like to see some assignments about reviewing others/editing poor writing. I think this is an important part of collaboration and also less time consuming than coming up with your own stuff."

> "It is better the white paper topic to be close to the reviewer's expertise field."

> "Decision-making strategies in choosing a "novel" idea; strategies to synthesize information effectively; acknowledging that this proposal writing process can be stressful/intimidating even for professors/professionals with experience and that it takes time and iterations to develop"

Open-ended responses suggest that while faculty participation in the review process was helpful, faculty participation across the board and throughout the module was too limited to have significant impact. Additional suggestions included more efficient collaboration of trainees (current and former) and faculty from the onset of the module and deliverables that could be reasonably completed for publication or viable proposal submissions.

> "One idea is to make it something that is actually useful and that the PIs stand to gain from. Perhaps we could do more collaborative research together as students and write on that. Or another idea is to collaborate on an engineering education/outreach activity in groups and write a paper on those results together as a process."

Trainees were also asked how they will apply what they have learned in their graduate studies and future career. One trainee out of twelve responses indicated they were unsure how they would use the information. For the remaining responses, in addition to the general skills of developing and writing a white paper others identified the module provided useful skills for theses, proposals, and business ventures. Sample excerpts include:

> "I am at the early stages of my PhD work and I will soon need to develop a proposal for my research studies. The skills I gained in this module have increased my chances of writing an acceptable thesis proposal."

> "…Continuing research will lead to new ideas and inspiration for more proposals."

> "I will be more compelled to seek others from other disciplines to collaborate and approach common research ideas/problems from different perspectives."

> "Next year, I will apply what I have learned to a new round of proposal writing (NSF & NDSEG etc.)

Informal evaluation was again conducted during meetings at project retreats. Increased faculty participation was identified as the most desired improvement for the module. Keeping the Independent Research module ahead of the Writing module was determined to be appropriate. Faculty, trainees, and external evaluators strongly felt that trainees should receive more structured education in the general area of their proposals due to the broad fundamental knowledge required to develop a research idea crossing over to a new disciplinary area. Also trainees and associate trainees completing their second year desired to work on an interdisciplinary, publishable project as their independent research deliverable. Therefore it was established that junior trainees would attend a survey course offered by Cornell University featuring lectures by interdisciplinary researchers about the most recent advances in the area of nanobiotechnology, and the fundamental science and research techniques that support them. Senior trainees organized themselves into two groups: one would develop a project in engineering education, and the other, perform a materials science investigation taking advantage of the trainees' different areas of expertise. A greater integration of the modules continued to be seen as a very important goal. Therefore the Ethics, and Teaching and Learning modules have also been redesigned to support the trainees' Independent Research module activities. The Year 4 Writing module will take place after the Teaching and Learning module (currently underway at the time of this publication submission) and will include deliverables based on and in support of the development of educational materials for students and teachers.

Evaluation process

As can be surmised from the above descriptions, although evaluation was a primary goal from the beginning of the project, approaches were developed and refined each year. In addition to annual evaluations by an External Advisory Council at the summer retreats, internal evaluations were developed through formative, informal discussions among trainees and the IGERT-MNM group as a whole and summative module surveys (allowing closed and open-ended responses). In Year 2, an initial survey was developed by trainees involved in the development of the module and advising faculty. In Year 3, the previous survey was revised by Engineering Education faculty and trainees based on general knowledge of survey design and ensuring that questions aligned with learning objectives outlined in the respective syllabus. Data was collected using Qualtrics, an online survey software. Bi-annual retreats included scheduled discussion times to reflect and discuss progress within the modules but discussions also occurred "offline" among committees responsible for the development of particular modules.

Challenges and conclusions

The book *The Formation of Scholars: Rethinking Doctoral Education for the 21st Century*" makes an urgent and pointed call for educators to "grapple with questions about what they do, why, and with what success (p 4) [24]". The authors point out that the purpose, vision, and quality of doctoral programs acutely suffer from a lack of well-defined and systematic assessment. Doctoral programs lack the structures and drivers needed for faculty and students to apply their scholarship practices to investigate their own purposes and actions as educators and learners. Besides missing the assessment culture, graduate education also suffers because graduate students, ready and willing to contribute as collaborators to shape their own professional preparation, are treated as mere recipients of a prescribed education program.

Therefore, it could have been expected that the high degree of innovation and level of effort required for the initial implementation and annual cycles of evaluation and redesign of the IGERT-MNM program would bring about resistance from participating faculty. Students, while being overwhelmed by the responsibility and freedom given to them, have generally embraced the model and value the opportunity to take on professional roles normally not present in their graduate programs. Nonetheless, the frank dialogue involving faculty and students, across disciplines and campuses, has been extremely rich, and has served to guide new iterations of courses and activities. Generally, faculty participants desire that project activities be more aligned with traditional graduate program expectations, while too busy to consistently assist in the extra work necessary to create new learning opportunities to form scholars prepared for the demands of the 21st century. Changes in the traditional research university value and reward systems will need to take place before overcommitted faculty can truly embrace graduate education reform.

The world of science and technology has been changing at an ever increasing pace. Ironically, graduate education has remained mostly unchanged in the midst of technologies altering and accelerating knowledge development and transfer, global competition threatening the U.S. preeminence, and intellectual breakthroughs more than ever requiring the integration of disciplines. The NSF-IGERT program makes a valiant effort to elicit responses from the academic community to develop models to assess and address what is required to equip scholars prepared to deal with the challenges of the modern world. By integrating engineering education with technical disciplines, IGERT-MNM has developed a framework in which faculty and students collaborate to create and assess education and training innovations. The project in many ways mimics the complex microcosm of graduate programs. As such, it serves as a valuable medium for studies of education and training innovations that go beyond isolated activities, providing opportunities for assessment of interconnected outcomes.

Moreover, the environment created in IGERT-MNM reflects the important finding of the learning sciences that "all forms of competence, in both thinking and skillful performance, develop through a process of guided experience, that in some ways resembles the traditional entry into professional life via apprenticeship (p. 23)[35]." In yearly cycles, IGERT-MNM moves trainees towards becoming expert interdisciplinary scientists and engineers through a process guided by the trainees themselves, while apprenticed to multidisciplinary faculty. Through the design, enactment, analysis and re-design of their learning activities, IGERT-MNM trainees practice the thinking patterns and skills of educators and researchers in a complex setting resembling that which they will encounter upon graduation.

In conclusion, we submit that the definition of design-based research by Wang and Hannafin (2005)[36] as "a systematic but flexible methodology aimed to improve educational practices through iterative analysis, design, development, and implementation, based on collaboration among researchers and practitioners in real-world settings, and leading to contextually-sensitive design principles and theories (p. 6)," should, in the case of graduate education, be extended to include the learners as collaborators.

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