Designing Capstone Experiences for Interdisciplinarity in Biomedical Engineering Education

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Abstract

Teamwork is a mainstay of today's workplace environment. This is especially true in healthcare and engineering fields, where work is so interdependent that teams are a dominant means to facilitating progress. Design and capstone courses are one of the places where biomedical engineering students develop skills needed for success in a team-based workplace. Our department participates in several levels of design across different programs. This includes Capstone in the Bachelors (BS) program, Professional Capstone in the Master of Engineering (MEng) program, and the Capstone Projects course in the College of Medicine. Having multiple disconnected levels of design presents numerous challenges, such as sourcing projects, structuring the scope of projects, and sharing resources both physical and personnel related. As a result, we elected to develop a shared resource model for projects across these programs to meet the needs of each program and to enhance the learning experience and professional preparation for students. In this new model, medical students develop projects based on needs identified during clinical rotations. Medical students then serve as clients for an engineering student team. Engineering teams are composed of MEng student project managers and BS student engineers, working on the project over the course of their capstone classes. Yet, the design and implementation of an interdisciplinary curriculum can be a challenge for instructors and students alike. These challenges may be due to differences in epistemological views, constraints of the higher education system, or a lack of frameworks that support interdisciplinary approaches. In this paper, we will share a framework for a design continuum of biomedically focused projects to provide students within our programs with a design experience relevant to appropriate academic, clinical, and industry roles and functions while optimizing department resources. To develop the collaboration, we applied an evidence-based scientific approach to conduct a human-centered design study integrated with insights from the literature to develop a more general understanding of the nature, form, and opportunities of cross-boundary coordination across multiple programs and multiple types of projects. Through multiple stakeholder analyses, we created an updated design experience where medical school students, masters, and bachelors' students worked together toward a common project goal. This paper summarizes the results from a one-year pilot of the collaboration. The framework includes defined competencies and deliverables for each program along the spectrum of engineering design. Additionally, quantitative and qualitative surveys along with the assessment of artifacts from the collaborative projects were used to assess the success of the framework. The strategies discussed in this paper may provide insight into the ways that collaboration among co-instructors can support the creation of learning experiences that overcome the challenges of isolated disciplinary experiences.

Introduction: History of Capstone Design

Healthcare and medicine will change dramatically in response to external factors such as inequities driven by rising costs of healthcare, the role of technology in medicine, and ethical dilemmas driven by increases in population and age-related diseases [1]. To anticipate and drive these changes, students training to enter the field must not only possess the technical abilities to solve these problems but also have the contextual and leadership skills to assemble teams to create solutions. To achieve these goals, we aim to break down the barriers between the technical aspects of engineering and the social and clinical aspects of medicine to produce bioengineers, who truly understand the clinical culture and environment [2]. Within the Bioengineering Department at the University of Illinois Urbana Champaign, the department, college, and unit structure, there are limited core or required experiences for engineering students to gain a more comprehensive understanding of the medical sciences or the practice of medicine unless they enroll in an external program or pursue a medical degree after graduation. Further, medical student courses are not open to auditing nor shared with the engineering school. The medical school uses a problem-based learning approach in small groups rather than larger science-based lecture courses. To this end, we created a new, clinically immersive educational experience to expose engineering students to their medical counterparts' clinical settings, culture, and education experiences. The new curriculum exposes engineering students to the clinical healthcare environment, and the process of disease diagnosis and management of human patients. This will fill a critical educational gap for inspiring engineering students toward translational medical research, entrepreneurialism, and healthcare [2].

Conceptions of engineering frequently suffer from a crippling form of technical-social dualism, separating the technical knowledge that engineers possess from the social implications that their knowledge engages [3]. This dualism is readily apparent in the traditional engineering curriculum with its heavy emphasis on math, science, and the engineering sciences, portraying engineering as a series of solely technical problems that need to be solved [4]. As engineers enter the workforce, this false technical-social dualism creates inner conflicts for practicing engineers as they end up spending most of their jobs solving problems in isolation from the context [5]. Meaning-rich, context-driven curriculum supports deeper forms of learning and the subsequent ability to translate that knowledge to new contexts in the future [6]. Traditional engineering training, without greater context of healthcare and medical need, social inequity, and understanding of the applications in the healthcare system, only allows engineers to create technology, which makes iterative steps toward impact in healthcare. Indeed, many research and industry approaches rely on creating useful technology and then finding healthcare or clinical applications for that technology. This approach has had many successes, but uptake in the medical community is slow and adaptation to meet clinical need is often a barrier to entry into the market [7]. By shifting the focus of capstone to needs observed in clinical rotations, and directly addressing the value of care to individuals and patients, the outcome can be relevant technologies, procedures, and systems created to solve critical problems identified with and designed for clinical users [7]. With the rapidly changing healthcare landscape as motivation, we set out to create an industry-relevant design experience for students at our university integrating multiple programs and stakeholders to enhance the learning experience and create an efficient and sustainable model for capstone design.

The Senior Design course that bioengineering undergraduate students complete at our institution is a one-semester course. The course is offered twice a year. In the integrated model presented in this paper, projects are managed by bioengineering Master of Engineering (MEng) Students over the year and each semester, a new and different team of undergraduates joins the project. This model relies heavily on thorough documentation by the team and cohesive project management by the MEng students. This handoff accurately models industry workflow and structure [8], [9]. Communication, teamwork, documentation, and project onboarding are all essential skills that students gain in this process. To facilitate this collaboration across project team members and capstone students, a curriculum toolkit developed during this project will be used to support student teams.

Capstone Design Course, Bioengineering 435 – Undergraduate Senior Design

This core required course provides an opportunity for students to apply their years of engineering undergraduate training in a clinically relevant design experience. Students earn four credits for successful completion of this course. This course prepares students for a real-world design problem, with an emphasis on the development, evaluation, and recommendation of alternative solutions subject to realistic constraints that include considerations of effective teamwork and technical communication, patents, quality controls, human factors, FDA regulation, professionalism, and ethics with an emphasis on preparing students for careers in bioengineering. Each year 85-95 students enroll in the course. Students assemble into project teams based on technical interests and skills.

Capstone Design Course, Bioengineering 575 – Master of Engineering

This capstone course is a required course for the 1-Year MEng Program. Students earn four credits for successful completion of this course. In this course, students work on a translational project to develop solutions for real-world problems utilizing principles of design, engineering analysis, project management, and business operations. Students engage with a client that is seeking solutions to an important problem. The solution that you propose to the client should be tractable, practical, and strategic. Each year 20-30 students enroll in the course. The emphasis is on preparing students for careers in engineering and project management within the healthcare sector.

Capstone Design Course, Carle Illinois College of Medicine – 4th Year Medical Student

This capstone project consists of teams of two fourth-year medical students as team leaders at this new engineering-based medical school. There are 32 medical students that will be enrolled in the capstone 2022-2023. In the academic year 2021-2022, 16 medical students participated in this integrated curriculum. We expect that enrollment will approach a steady state in this fourth year of the school's operation. The students will design, fabricate, and develop a business plan for a broad-scoped project that aims to solve a need that the students have identified during their required clinical rotations in their third-year year.

Exploring opportunities for the integrated model

Concurrently running three capstones is resource intensive (projects, course staff, design labs). To understand the opportunities and challenges of creating this integrated model, stakeholders from each course collaborated to lay out the specific objectives of each course, timelines, practicalities of the course offerings, and technical content. By integrating the three courses, we found ways not only to become more efficient in the delivery of instruction but also to benefit students (Figure 1). These benefits provide the students with the opportunity to gain collaborative practice skills including responsibility, accountability, coordination, communication, cooperation, autonomy, and mutual trust and respect [10]. It is critical to note that the independent learning objectives and goals for each cohort of capstone courses and students were initially different. The first goal of establishing the collaboration was to identify both overlaps and differences among the goals and objectives of each program. Table 1 lists the key objectives for each capstone course. Overlaps and differences are documented along the row of the table.

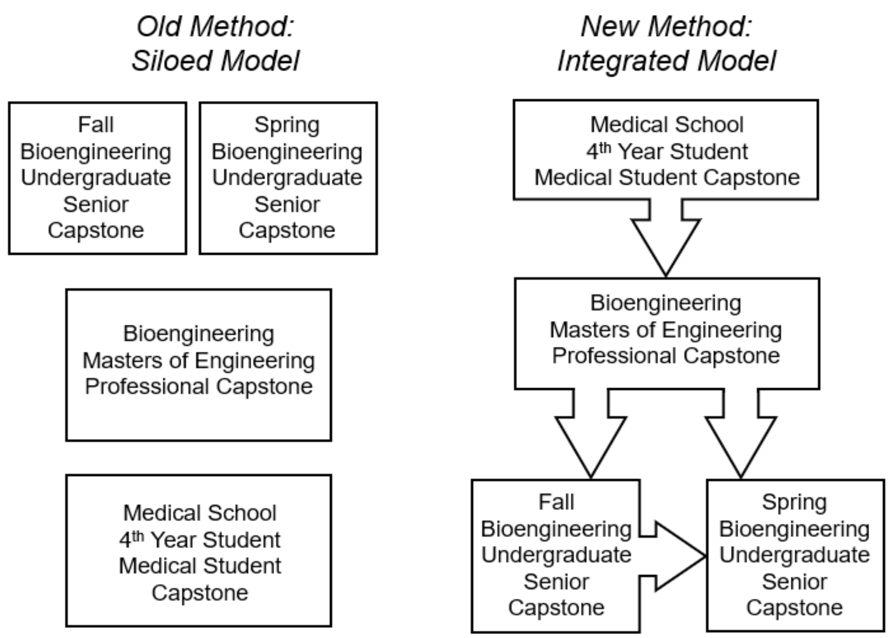

Figure 1. Schematic representation of old and new models of capstone design across three programs.

Table 1: Capstone Course Learning Objective Mapping and Comparison. Each column represents a program. Each row represents a learning objective of that program. Some learning objectives only exist in one program. In others, similar objectives are attained in multiple programs. Course instructors of each program aligned the objectives through multiple iterations of comparison and discussion.

Bioengineering Undergraduate Senior Capstone	**Bioengineering Master of Engineering Professional Capstone**	**Carle Illinois College of Medicine 4th-Year Medical Capstone**
Identify, formulate, and solve complex engineering problems by applying principles of engineering.	Gains skills to facilitate an engineering project from problem discovery to appropriate deliverables.	Identify a problem or deficiency in the delivery of healthcare that can be improved or solved with an engineering approach.
		Design a technology-based solution to a challenging contemporary healthcare delivery problem, within realistic constraints and utilizing appropriate standards.
Apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare.	Gain skills and knowledge on client relationship building and client management during project execution.	Apply and/or develop new technologies to healthcare challenges in ways that recognize the needs of our time set forth by IOM, NAE, PCAST, and medical societies.
Communicate effectively with a range of audiences.	Communicate the importance of the problem and the technical solution to a group of engineering, clinical, and business professionals.	Communicate the importance of the problem and the technical solution to a group of engineering, clinical, and business professionals.
		Demonstrate effective written technical communication skills through final reports.
Recognize ethical responsibilities to make informed judgments.		Understand professional and ethical responsibility, particularly ethical challenges relating to human subject's research.
Perform the above with regard to global, economic, environmental, social contexts.		Demonstrate the broad education necessary to understand impact of engineering solutions in a global, economic, environmental, ethical and societal context.
	Demonstrate an understanding of regulatory approval process as needed for the solution proposed through the capstone project.	Demonstrate an understanding of regulatory approval process as needed for the solution proposed through the capstone project.
	Identify the intellectual property pathway and conduct competitive and market analysis of proposed solutions.	Identify the intellectual property pathway and conduct competitive and market analysis of proposed solutions.
Function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.	Gain knowledge and effective practice of teamwork and effective project management.	Identify and form a team of interdisciplinary collaborators across campus and Clinical Partners to solve a clinical problem that has been identified.
		Develop a network with individuals and groups from multiple disciplines, share information effectively, and motivate individuals to collaborate on the project.
Develop and conduct appropriate experimentation, analysis and interpretation of data using engineering judgment to draw conclusions.	Conduct a full design review process outlining the proposed solution, technical details, timeline, cost to produce, requirements and verifications, and safety and ethical considerations through a collaborative team-based approach.	Conduct a full design review process outlining the proposed solution, technical details, timeline, cost to produce, requirements and verifications, and safety and ethical considerations through a collaborative team-based approach.
Acquire and apply new knowledge as needed, using appropriate learning strategies.		

After outlining the learning objectives, we understood areas in which objectives could be met in all courses and areas in which one cohort would lead to gaining that competency. For example, an objective in the medical school capstone course is to "Develop a network with individuals and groups from multiple disciplines, share information effectively, and motivate individuals to collaborate on the project". In this case, medical students would be responsible for assembling a diverse team of experts to support project progression. For undergraduates, one objective states, "Recognize ethical responsibilities to make informed judgments". Students in this course are taught modules on ethical case studies and have assignments related to demonstrating the application of ethics principles and the engineering code of ethics to their project.

The next step in aligning the courses was to create a timeline of course activities to ensure that all objectives can be met including presentations, design reviews, and project handoffs at different stages. Figure 2 shows the timeline of how each course interacts with the design project within their courses.

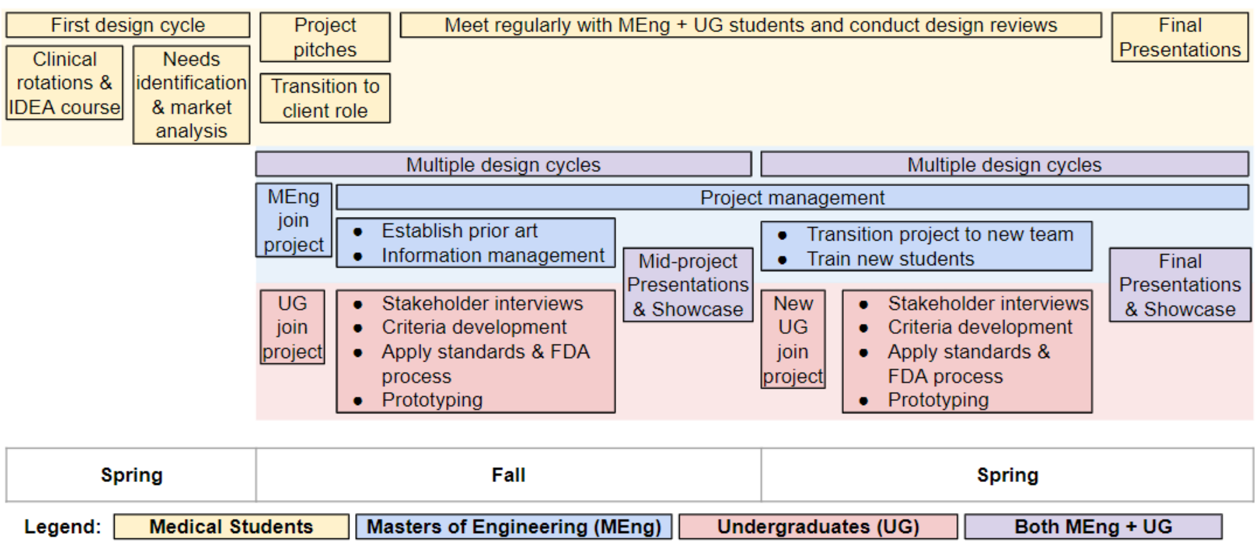

Figure 2. Flow diagram of how the programs/courses will collaborate.

Development of Project Ideas

Medical school students engage in two courses as part of the Capstone experience. The first is called Innovation, Design, Engineering and Analysis (IDEA). In this course, third-year medical students generate new ideas to improve healthcare challenges observed during each clinical clerkship. A team of engineering and clinical faculty mentors evaluate project proposals to generate a set of projects that are of high need and clinical relevance and also appropriately scoped. Selected projects may be a new approach to a technique, new technologies or new treatment. During the Spring of the third year, medical students research the problem identified during their clinical rotations, propose a solution, and then recruit and lead a cross-disciplinary team that includes bioengineering students and business student consultants, to develop a new prototype or process with the goal of changing the practice of medicine and improving patient outcomes. In the following Fall semester, medical students deliver 5-minute pitches to recruit engineering MEng and undergraduate students to the project.

Formation of Engineering Capstone Experience

The MEng and undergraduate capstone courses meet together to facilitate teamwork during open lab times and reflection on lecture topics. In the first week of class, project clients (from Medical Capstone previously described) pitch projects to the class. Pitches give an overview of the project background, the identified need, and practical details about the type of prototype the client is looking for. This information is used by students to vote for projects. Course instructors staff projects with 1-2 MEng students and 3-5 undergraduates depending on project needs, enrollment, and interest. From here both MEng and undergraduate students use skills previously learned in the curriculum and a series of modules taught in this course to confirm the project need through stakeholder interviews, prior art investigation, and development of design criteria in collaboration with medical school students. Topics covered in the MEng + undergraduate capstone course are detailed in Table 2. These topics are primarily new to all undergraduates within the context of capstone design. For example, undergraduates learn ethics in a first-year course through project-based work[11], but it is focused broadly on the field of bioengineering, while in this course the focus is on engineering design and specific challenges they may face in their project and teams. MEng students may have taken courses in these topics at their undergraduate institution if they majored in engineering. MEng students attend lecture in the fall semester and can reinforce topics when they are delivered in the second semester to the new team of undergraduates. Additionally, MEng students are concurrently enrolled in a business/project management course. The management course includes principles of design, management, and improvement of business operations and product innovations. Strategies and techniques for managing processes, projects, process improvement, and new product development are emphasized. Additionally, students learn how to define and analyze strategic problems stemming from innovation and technological change and to identify sources of competitive advantage. Project management skill development was evaluated and assessed by MEng instructors.

Table 2. Topics covered in Bioengineering Capstone course through modules and workshops.

Lecture topics
Project Management
Introduction to Biodesign
Intellectual Property and Patents
Engineering Standards
FDA and Regulatory
Ethics & Inclusion in Design
I-CORPS Customer Discovery Framework
I-CORPS Value Proposition
I-CORPS Customer Segments
Workshops
Team Contracts
Computer Aided Design for Capstone
Arduino Programming: sensors and wireless communication
Silicone Molding and Prototyping
Mobile Application Development

When student teams are formed, around week three of the semester, the first assignment is a collaborative assignment with MEng and undergraduates to develop a team contract. This contract facilitates setting meeting schedules, outlining roles within the team, norms, and creating a timeline of projected tasks and events. While MEng students are primarily in a project management role, if they have a particular technical skill or interest to learn, they may participate in the physical prototyping. Halfway through the semester, students are asked to reflect on the team contract and areas for improvement by answering the following three questions: (1) What is your general feeling about the dynamic of your project group so far this semester? [Likert scale], (2) Take a moment to review your group's contract. How well do you feel your group (as a whole and as individual members) is adhering to the guidelines you agreed on in your contract? [Likert scale], and (3) Is there anything specific that you think you or your group needs to work on to have a better experience in the remaining weeks of the semester? [Free response]. Responses from the first year of implementing the integrative model of capstone are shown in Table 3. When analyzing the open response question, responses were anonymized after the completion of the course by a course assistant. Deidentified data was categorized and discussed to ensure interrater reliability and quality informed by the Q3 framework[12]. More than half of the students reported a positive experience so far. When asked to identify areas for improvement, 35% of the responses were related to communication. This was identified as desired improvements in communication overall, across the programs, with clients, or a lack of understanding of the exact roles of the different cohorts. In part lack of understanding is due to the open-ended nature of the courses and the ability for teams to assign and organize roles, however, after this feedback, course instructors were very intentional about outlining specific roles that each cohort is responsible for and qualitatively that has improved expectations across both programs. Additionally, at the end of each semester, the CATME peer evaluation tool was used to provide a structure for peer feedback within the teams.

Table 3. Themes from student feedback.

What is your general feeling about the dynamic of your project group so far this semester?		
Response	**Count**	**Percentage of total responses**
Very positive	21	53.8
Somewhat positive	13	33.3
Neutral	2	5.1
Somewhat negative	3	7.7
Very negative	0	0
Total Responses	39	
Take a moment to review your group's contract. How well do you feel your group (as a whole and as individual members) is adhering to the guidelines you agreed on in your contract?		
Very well	23	59.0
Somewhat well	11	28.2
Neutral	2	5.1
Somewhat poorly	3	7.7
Very poorly	0	0
Total Responses	39	
Is there anything specific that you think you or your group needs to work on to have a better experience in the remaining weeks of the semester?		
Communication (general)	5	12.5
Communication (with UG/MEng)	3	7.5
Roles of MEng and UG	2	5
Communication (with client)	3	7.5
Working ahead of deadlines	6	15
Working together more	3	7.5
Technical progress	4	10
Equal participation	2	5
Flexibility	1	2.5
A positive comment (Example: "I love working with my group!"	3	7.5
Nothing to work on	8	20
Total Responses	40	

Along with the thematic assessment of the student experience, the MEng student project managers were asked to reflect on their experience managing the project with two different teams of Senior Design students. Some of the feedback from the MEng is highlight as follows:

- For some of the project teams, the Senior design students had known each other since freshman or sophomore year. The challenge for the MEng student was building rapport with the team and gaining their trust.
- Many of the team members expressed lots of pride in working on a project that can impact people's lives.
- The project provided an opportunity to overcome fears of leading a team and gaining confidence in public speaking.
- Gained valuable lessons in conflict management and resolution.
- Better understood the importance of open and collaborative communication.
- Better understood the impact of clear project goals on self- and team- motivation.

Many of the points highlighted in the student reflection are potential challenges that may be encountered in the workplace.

Project Outcomes

At the end of the fall and spring semesters, MEng and undergraduate students present projects in two events, a 30-minute technical presentation, and a gallery walk style showcase event. A pilot collaboration across these programs resulted in medical innovations presented in two conference papers [13], [14]. Figure 3 shows the evolution of prototype designs in one year across two semesters. This also highlights the ways in which a new undergraduate team in each semester works on the same project but iteratively improves the design and prototype of devices. Instructors anecdotally noted that project prototypes increased in complexity after the collaborative pilot.

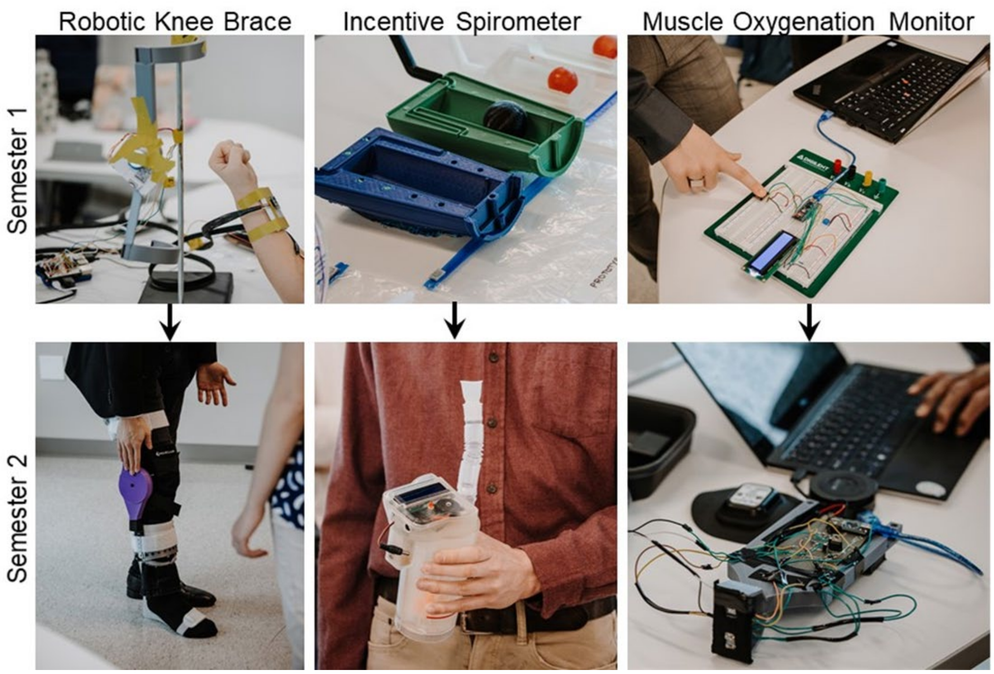

Figure 3. Photos showing the evolution of three capstone project prototypes that are carried across multiple semesters.

This new approach requires the development of a suite of activities related to curriculum design, clinical experiences, and assessment approaches to support the integrated education. The motivation for this curricular redesign is focused on replicating organizational structures that students will experience post-graduation and providing opportunities for them to develop relevant skills. Figure 4 shows a mapping of the skills and interactions across programs. As the program evolves, evaluation data will be used to determine if this transformative curriculum develops engineers with the desired attributes to increase the translation of clinically related engineering designs.

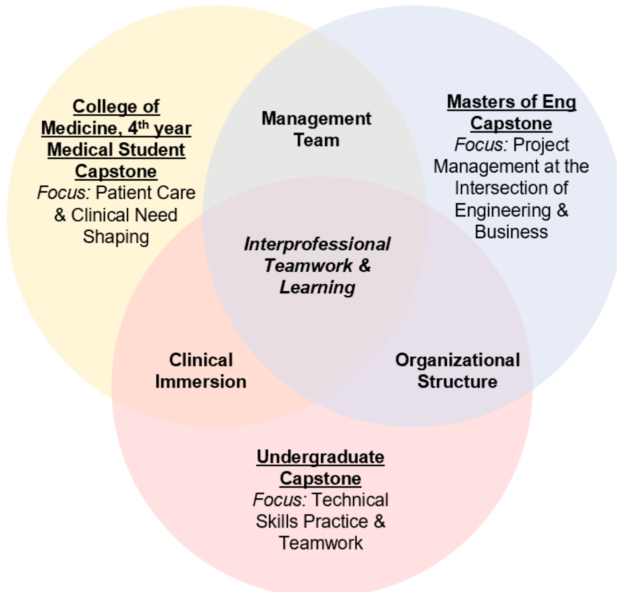

Figure 4. Mapping of capstone courses and overlapping interactions and skills across programs.

Reflection and Future Work

In developing this curriculum, we did learn that this shared-resource model has its challenges. When first planning this collaboration, 1-2 faculty members from each program spent a summer planning in regular meetings and a one-week intensive workshop during that same summer to plan the curricular collaboration. The summer intensive workshop leveraged human-centered design strategies to develop a curriculum that meets the needs of stakeholders (programs, administration, instructors, teaching assistants and students) in different courses. During implementation, teaching assistants provided feedback to instructors to inform course improvement. In year 2 of the project, adaptations addressed some of these challenges. Some of the challenges identified were (1) alignment of assignment due dates, (2) lack of some understanding of the roles of the undergraduate and MEng students, and (3) identifying points of engagement with the medical students during their 4th-year clinical rotations. In year two we created better alignment among assignments through communication of course instructors, presented students with a chart illustrating the roles and responsibilities of each group, and regularly check-in with teams about communication challenges to address them early. The streamlined process of sourcing and sharing course projects was noticed by all stakeholders. Sourcing capstone projects is a significant time burden throughout the academic year and summer for faculty, which can now be shared. These changes have resulted in smoother workflow across all programs. We plan to continue iterative improvements to the course design to optimize student learning opportunities and success in the course. This initial pilot represented several of the nuances and challenges of interprofessional collaboration. Overall, we see improvements in final project deliverables and prototypes when compared to the siloed model and many additional opportunities for students' skill development when compared to opportunities in the old curriculum.

Acknowledgments

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