Towards Integrating Graduate Research and Education with "Internal Research Internships": Experiences and Assessment

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Abstract — *We describe our efforts towards integrating graduate-level research and education in a highly interdisciplinary laboratory environment. The educational innovation we wish to evaluate is the "Internal Research Internship," in which a graduate student with an established research project is placed in a host laboratory for a semester or more to work in a distinct, but complementary, area. The test bed for our study is the third course of a three-semester sequence in microsystem design and fabrication. Participants in this class lead teams of less experienced students, to accomplish a difficult design challenge. Each of five teams is responsible for a critical component of a sophisticated device; the five leaders are responsible for coordinating and integrating the separate efforts. Partial success should be attainable through interdisciplinary communication and teamwork. Complete success represents work at the level of the current state of the art. In this study we focus on interactions between the team leaders. In particular, a cell biology graduate student was brought into a microfabrication laboratory specifically to work with a physicist and an electrical engineer leading teams developing a DNA amplification chamber and a target DNA pre-filter. Initially awkward, inefficient and unproductive, the relationship between these students gradually became fluid, respectful and ultimately extremely fruitful. Unanticipated benefits also sprang from interactions between the biologist and other team leaders, and with the graduate education student assigned to assess the effectiveness of the project.*

Index Terms — *microsystems, interdisciplinary research education, internships, peer mentoring.*

INTRODUCTION

We describe integrating graduate-level research and education in a highly interdisciplinary microsystems laboratory environment. The framework we use is based on our extensive experience with industrial internships. By applying the industrial template to internship-like positions within university research labs, we hope to incorporate many of the educational benefits of industrial experience into the traditional graduate research model.

Our eventual goal is to develop the "internal internship" approach for broad application in the sciences and engineering for advancing interdisciplinary research. The American Association for the Advancement of Science [1] and the National Research Council [2] advocate collaboration among students from multiple disciplines for fostering innovative ideas. As a developmental test bed, we have incorporated this approach into the final two courses of our graduate three-course microsystems curriculum. In these two courses [3], [4], "Topics in Microsystems" and "Advanced Topics in Microsystems," three levels of participants—each playing a role from the industrial milieu—interact to accomplish a significant research milestone. The faculty members teaching the course are the first level, representing a client with specific technology needs. The faculty—from a variety of science and engineering departments, plus a specialist in science education—define the functionality of the device to be constructed, and a set of design constraints such as size, cost, power consumption, etc. Students in the Advanced Topics course are the second level, representing technical management. They are chosen for the course either because they have broad knowledge and significant experience in the microsystems field, or because they possess deep expertise in a specific area central to the target device. These students work as a team to design a device responsive to the requirements of the Clients. We call students from the Advanced Topics course the "Team Leaders." This refers to their role directing the small teams of two or three students each from the Topics class that make up the third level.

Students in the Topics class have a working knowledge of microfabrication techniques, and are either graduate students or advanced undergraduates from science or engineering backgrounds. These students represent practicing engineers, and it is their responsibility to carry out the actual device fabrication and testing. We call them the "Team Members." Component design is entirely handled by the Team Members, with integration aspects overseen by the Team Leaders working as a group. The Clients receive weekly briefings from the Team Leaders where feedback is given and potential problems are discussed. Formal presentations are made approximately monthly by the collected memberships of both courses.

This report focuses on the experience of the students at the second level, that is, on the Team Leaders. Because they are all graduate students with significant research experience, because they are placed in a team setting with a strongly interdisciplinary flavor, and because of the high degree of peer interaction that their duties require, their environment is very close to what we plan to achieve in our internal internship project. Previous implementations of this course structure [3] had Teams competing to develop similar technologies. Here, we combine the Team Leaders into one unit, with a common goal, thereby emphasizing team-building aspects. The result is a far richer learning environment for the Advanced Topics students.

The device they are asked to produce is a sensor capable of determining whether a small sample of DNA contains a specified base sequence, for example one characteristic of a specific organism. The device requires a number of steps, including sample preparation, screening for the target base sequence, amplification through polymerase chain reaction (PCR), and signal processing. Exact details are left to the student design team. All functions, plus the associated fluid-handling infrastructure, are to be incorporated on a single chip. This is a challenging project, involving several current research areas from the laboratories of the affiliated course faculty. The groups and academic areas of the team leaders are included in Table I. Although we attempted to utilize students' skills so that they would have their best chance at succeeding with the device goals, we were also interested in allowing them to expand into areas beyond their "comfort zones".

Research success is defined by the degree of functionality of the resulting device. Partial research success is defined by the development of key processes, the design of important device components, etc. Key non-technical goals for this group include development of team leadership skills, and experience with peer interaction in an interdisciplinary environment. Success in these areas is assessed using interviews with the students, journals that they keep, and observation as they interact with each other, with their Team Members, and with the faculty Clients.

DESCRIPTION OF THE DNA-BASED SENSOR

The functional design of the device is shown schematically in Fig. 1. The device is made of two patterned layers of poly (dimethyl) siloxane (PDMS) on a structural glass wafer. The first area encountered by the sample is the capillary, which is functionalized to preferentially immobilize target DNA [5]. The purpose of the capillary is to filter out, through capture, the desired DNA for amplification and detection. The capillary is placed into the chip at the time of application in order for the user to customize the DNA selection. Similarly, the PCR primers are to be injected at the time of use to maintain flexibility. PCR amplification [6] is done on chip, requiring heaters and temperature control. The amplified product is transferred to the liquid core waveguide (LCW) [7]. The LCW is made of Teflon® AF, which has an index of refraction of ~ 1.29. This is lower than the index of water, so that when the LCW is filled with a fluid such as water, fluorescence generated within a cone of solid angles will undergo total internal reflection. Light emerging from the end of the LCW is captured by an optical fiber (not shown in Fig. 1) and passed to a photodetector. An expanded schematic of the LCW is shown in Fig. 2.

On-chip peristaltic pumps [8] were also designed into the system in order to transfer sample and other fluids between the functional areas. An interesting aspect of this device is that the students designed it to function based on a single peristaltic pump. This minimizes footprint but requires a clear understanding of the flow sequences to be used. Their implemented design is clever, but requires further refinement. The sequence of Fig. 3 demonstrates the pumps in operation moving a fluorescent test fluid on a prototype device. Figure 4 shows how the functionalized capillary and LCW were sealed into the device using injected PDMS "dams." Fluorescent fluid can be seen moving through the top tube without leaking around the outside of the capillary.

Illumination of the channel is through a series of light emitting diodes (LEDs). Because LEDs are now commercially available in the blue and near-ultraviolet range, their compactness, low power consumption, and low operating temperature make them ideal for incorporation into fluorescence-based sensors.

Each group was instructed to produce an initial design, address integration issues with the other groups, and present their overall design to the Clients for approval and input. Each group was expected to create a test bed for their component of the overall device, so that they could evaluate its effectiveness and troubleshoot without any delays incurred by waiting for other groups to complete tasks. When all components were working, the final device integration was to be accomplished.

CASE STUDY

As a case study, we discuss the role of the sole Biology graduate student, J—, in the internal internship. Rather than lead a particular team, J— was expected to act as a Research Intern to the leaders of Teams 2 and 3 (see Table I), combining their fabrication knowledge with his biological expertise to produce PCR and DNA capture schemes, and to spend minimal time with the other Teams. As it turned out, the level of biology required made J— the research mentor to the Leaders of Teams 2 and 3, while interacting significantly with the others. We focus here on his experience because of this comprehensive role and because his experiences were both Internal Internship *host* and *guest*.

In his role as mentor, J— had contact with two groups. The first group was responsible for modifications of a glass capillary for selective binding of target DNA. This is a critical step. The subsequent PCR process preferentially amplifies the target DNA. However, PCR is sufficiently robust that a sample containing large populations of untargeted DNA will also produce non-specific amplification giving a false signal. Therefore, a filtration step is needed to minimize contamination. The filtration is accomplished by first binding an oligonucleotide to the inner walls of the capillary. Samples containing target and unwanted DNA are brought into the capillary, where the target preferentially binds. Following a rinse step to purge unbound "waste" material, the bound species are released by heating the capillary to 95 °C and transferred to the PCR chamber. The capillary part of the design includes glass surface modification, fluid exchange, temperature control, and standard (i.e., off chip) PCR amplification to determine success of the filtration step.

The team responsible for designing and testing the on-chip PCR system was the second group mentored by J—. The PCR team designed the chamber along with external heating and cooling, each placed in contact with the chip but not in immediate contact with the fluid. This way, heater and cooler were part of the permanent infrastructure. The PCR process requires cycling the temperature between 65 and 95°C, while supplying the amino acid building blocks and primers. The design requires temperature measurement and control, learning standard PCR methods to determine if tests were successful, and interfacing with the microfluidics group for sample transfer.

The design and implementation of these components is clearly interdisciplinary. Before transferring the approaches to the teams, J— first needed to fully research, understand, and experiment with these techniques himself. Because he had to respond to the design direction of his guests in order to act as an effective mentor, he became familiar with methods not central to his own research. Thus J— gained new capabilities in his *own* field as a consequence of taking this interdisciplinary course! His mentoring of the engineering and physics students began by identifying archival articles at the appropriate level. This was not simple, since J— is accustomed to working with fellow biology students, with a firm grasp of the concepts, language, and methods commensurate with years in the field. In contrast, the engineering and physics students had only introductory freshman level courses in their undergraduate curricula, and years had passed since that general exposure. With some perspective, both mentor and guests learned the value of interdisciplinary communication through this exercise. Through combinations of in-class group presentations and during the practical walk through at the end of the semester, we determined that the teams had learned a substantial amount about the biochemistry of their project components. We view them as conversant in these topics, enabling the team members to conduct interdisciplinary research. This qualifies the internal internship approach as successful.

J— was also in the position of being an intern in this project by working with the microfluidics and optics groups. From the microfluidics group, J— learned about fluid properties at the microscale. From his own reflective journal, it was clear that he did not appreciate in advance the difficulties of such aspects as mixing. Here, the small characteristic length scale gives small Reynolds number and prevents turbulent mixing. Therefore, absent other steps to enhance advective transport, mixing is driven by the relatively slow process of diffusion. This topic is important for the PCR process, where amplification steps require the intermixing of sample and the nutrient/primer solution. J— learned more about this through discussions with and demonstrations by the pump group. The optics group worked on all aspects of fluorescence detection. The fluorescent tags, incorporated into the target DNA during PCR, are illuminated using LEDs. The resonant excitation wavelengths and emission spectrum are characteristic of the fluorescent tags, and fluorescence imaging is a standard method in biological science. J— went from being a user of this method to having a detailed understanding of the fluorescence process. The detection of small sample volumes, necessary to obtain a result in the minimum number of PCR cycles (processing time), requires sophisticated detection schemes. In the current context, a liquid core waveguide was used based on commercial Teflon® AF tubing. Therefore, in order for J— to fully appreciate the fluorescence detection in a microfluidic setting he learned about waveguides and basic optics, minimum detection levels, and methods for testing them. This broadened his experience and prepared him to communicate with engineering and physics students on a much more viable level.

It was very clear to us by the end of the course that the bi-directional flow of capabilities was functioning. For a course in design and implementation of biological sensors, we feel that it was essential to have a biologist strongly involved in the course. In fact, it would be preferable to have at least two to better distribute the workload. It is also important, of course, to see how individuals other than J— function in this setting. While we feel that the experience is generalizable, J— did have some qualities, most notably military training, that may have made him better prepared to handle it. At the same time, we feel that the five other students involved in this process also became clearly better equipped to collaborate effectively in interdisciplinary research. We intend to observe the careers of each of these students to see if they use their interdisciplinary communication skills, and whether they impact their research efforts.

ROLE OF ASSESSMENT

This project placed the graduate students in a situated learning environment [9], [10], where they worked on interdisciplinary projects requiring the expertise and talents of all participants. An assessment team of students in Science and Engineering Education evaluated the effectiveness of the structure. They focused on the types of learning and knowing that occur in the peer-to-peer setting. The main reason for this was to extrapolate that experience onto the similar relationship between host and guest doctoral students in an Internal Internship. Thus far, evidence has been provided that supports a connected knowing being established where these six students' knowledge is being facilitated by and co-constructed with the other graduate students in the class.

The effectiveness of the Internal Internship approach was assessed through observations of classroom and group meetings, interviews, and reflective journals. To ensure that the latter were kept up to date, they were made part of the course grade. Students were assured that the interviews and reflective journals would be kept confidential, and that the instructors responsible for the course grades would have no access to the journals outside of sanitized feedback. At the time of this writing, all assessment completed is formative. Evidence in the form of journal entries, survey responses, and videotaped and transcribed class meetings display facilitated learning.

To accomplish the assessment tasks, two education doctoral students participated in the program. Neither student had a science background. They were not enrolled in the course, but were allowed complete access. Class sessions were audio recorded, reviewed, and transcribed. Journals were reviewed on a bi-weekly basis. Several interviews were conducted. A very important finding of this approach was that the education students learned what students were thinking in a way that grade-determining professors could not expect to. Observations included: 1. Group communication was markedly improving. 2. Based on one student's recommendation, meeting notes would include action items to be distributed class wide for better integration. This helps in defining roles and responsibilities. 3. Peer instruction on technical issues was proceeding in the group leader meetings and in the individual task meetings. 4. Students policed each other for understanding and followed up with further discussions to clarify misconceptions. The reflective journals provide us with evidence of improved communication skills. We observe that this improvement over the semester was instrumental in developing the cooperative technical skills needed to make progress on the device.

There were also troubling observations: 1. Students were frustrated that their peers weren't versed in their area, or weren't keeping up with reading they assigned. Students resolved these issues both on their own, with advice from faculty, and with the help of faculty. It was also necessary to remind them and ourselves that specialization happens relatively early in most undergraduate curricula. 2. Several students were likewise frustrated that faculty could not provide hard information on some questions, but recommended further experimentation to find an answer. This shows that they did not fully appreciate that the course was research oriented – faculty are also interested in finding the answers to difficult questions. This is in stark contrast to standard courses in which well-known methods and problems are primarily addressed. This distinction will be better drawn in the future.

We also find evidence that the education doctoral students learned from this experience. This learning included concepts from both biology and engineering, and we were gratified that everybody was benefiting from the experience. However, a keen observation was expressed in a report, in which it was stated:

> "I begin to see the beauty of interdisciplinary learning. [...] I was really amazed by the lively interaction these team leaders demonstrate especially during those times when they have to discuss the pros and cons of a particular action. Since everyone in the group comes from different fields with varied expertise, neither one is an authority. Everyone is both a teacher and a student as each of them has to share their own knowledge in thinking, planning, designing, testing, implementing, and redesigning the project whenever there is a need to do so. Nobody knows everything and everybody has to share something. [...] I'm saying this because I saw it myself how students in physics and in biology would work together to address for example the problem of DNA sample preparation and bonding in the device which the group is working on. In another occasion, I also witnessed how the Engineering students would have to struggle to come up with a design (i.e. liquid-core waveguide) to detect the presence of DNA. [...], as a doctoral student in Education I can say that my exposure to this kind of learning environment has significantly broadened my view on instructional techniques; that the benefits of learning are better maximized when the teacher does not monopolize the teaching of the subject; that the benefits of learning are enhanced when synergy and creativity among the students are fostered, where their curiosity is best accommodated by a right amount of tolerance."

This observation, made by a student previously uninitiated to the value of interdisciplinary research and education, provides strong, independent verification of the importance of further developing the Internal Research Internship concept.

SUMMARY

We have explored the use of Internal Research Internships by placing a biology graduate student in a peer-mentoring learning environment in a team-based microsystem design and fabrication laboratory course. The interaction between this student and others, including graduate students in physics, electrical and mechanical engineering, and education, led to a rich and productive educational experience. In addition to becoming more familiar with technical skills from other disciplines, the students learned to communicate with researchers of different backgrounds. They became more comfortable in their own field, through the struggle to make their knowledge accessible to others. While this is a limited sample, it is extremely positive and encouraging, and we see ample evidence to support pursuing the concept.

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FIGURES AND TABLES

TABLE I
TEAM TITLES AND THE ACADEMIC MAJOR OF THE TEAM LEADERS.

NUMBER	TEAM TITLE	MAJOR
1	Mixing, Injecting, Sample Preparation	Mechanical Engineering
2	DNA Sequence Pre-selection	Electrical Engineering
3	On-chip PCR	Physics
4	Microfluidic Design/Waveguide	Mechanical Engineering
5	Optics, Illumination, Detection	Electrical Engineering

FIGURE. 1
SCHEMATIC CUTAWAY OF THE DNA SENSOR CHIP FULLY DESIGNED BY THE STUDENT GROUPS IN THE “ADVANCED TOPICS” COURSE.

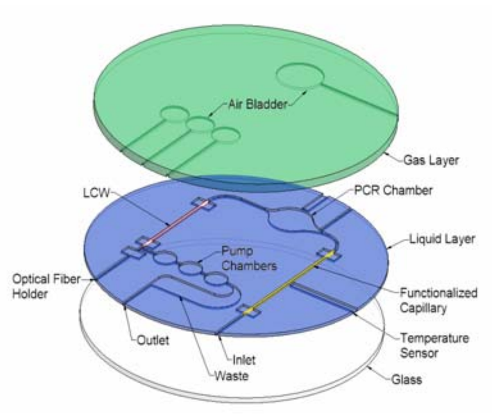

FIGURE 2.
SCHEMATIC OF THE LCW FUNCTION. EMITTED FLUORESCENT SIGNAL (GREEN) AT A SUFFICIENT SMALL ANGLE OF INCIDENCE UNDERGOES TOTAL INTERNAL REFLECTANCE AND IS CAPTURED BY THE COLLECTION OPTICS.

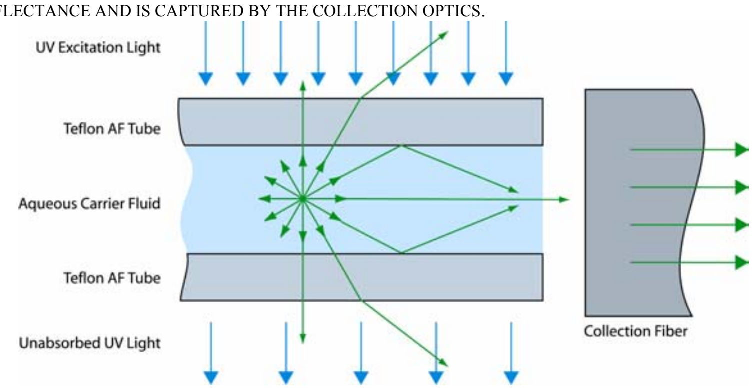

FIGURE 3.
PERISTALTIC PUMPING OF FLUORESCENT TEST FLUID. THE RECTANGULAR CHAMBER ON THE RIGHT OF THE LAYOUT IS BEING FILLED. THE TUBES SUPPLY PRESSURIVED AIR TO CYCLICALLY COMPRESS THE THREE PUMP CHAMBERS.

FIGURE 4.
CHANNEL SEALING SYSTEM. THE DEVICE SHOWN CONTAINS THREE TEST STRUCTURES, OF WHICH ONLY THE TOPMOST IS BEING USED. IN THE THREE-PICTURE SEQUENCE SHOWN, THE DEVICE IS INITIALLY EMPTY, THEN FLUID STARTS TO FLOW FROM LEFT TO RIGHT. THE EMBEDDED CAPILLARY IS ROUND WHILE THE CHANNEL IS SQUARE, BUT NO FLUID LEAKS AROUND THE EXTERIOR OF THE CAPILLARY.