The Global Challenge in Neuroscience Education and Training: The MBL Perspective

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The greatest challenge in moving neuroscience research forward in the 21st century is recruiting, training, and retaining the brightest, rigorous, and most diverse scientists. The MBL research training courses Neurobiology and Neural Systems & Behavior, and the Summer Program in Neuroscience, Excellence, and Success provide a model for full immersion, discovery-based training while enhancing cultural, geographic, and racial diversity.

> Thank you for changing my life. I am a scientist today in no small part because of my summer at Woods Hole.—2008 Alum

> It was one of the most transformative experiences of my life. My confidence and ability to do science skyrocketed during and after the course, and I met many people with whom I am still in regular contact (both personally and professionally).—2011 Alum

To achieve a comprehensive understanding of how the brain works will require an unprecedented transdisciplinary collaboration of scientists around the globe. To accomplish this, we must "attract, train, and nurture" the brightest and most diverse trainees across the fields of biology, psychology, chemistry, physics, computational science, engineering, and mathematics (Akil et al., 2016). Furthermore, as our efforts to understand the brain progress, we must rapidly disseminate the research tools and techniques that are developed out of programs such as the NIH BRAIN Initiative. While this could be done in the laboratory of a scientific investigator or as a course at a university or college, there are significant challenges: training in an individual scientist's lab provides hands-on experience but is limited in numbers trained, whereas giving lectures or seminars reaches many, but cannot provide hands-on training. Thus, a complementary approach is that modeled by short, but intensive, courses offered at Cold Spring Harbor, Jackson Laboratory, and the Marine Biological Laboratory (MBL). These courses recruit 15–50 graduate students/postdoctoral trainees/junior faculty members and provide intensive, hands-on training for 2–8 weeks in select scientific topics. These have a strong track record in producing the new leaders in many biomedical fields such as cell biology, developmental biology, microbiology, genetics, and neuroscience. Furthermore, these 15–20 students, combined with faculty and teaching assistants, create a cadre of messengers, 20–40 in number, who can return to their home institutions well equipped to be ambassadors for the study of the brain.

The model of education and research training developed at the MBL in Woods Hole, Massachusetts, epitomizes the kind of social engineering and education that will drive the intellectual and technical pioneering required for the comprehensive understanding of human brain. The environment during summers at the MBL is a dynamic assembly of an intellectually, ethnically, racially, and geographically diverse community of investigators and educators who gather to craft the next generation of research scientists. From its founding in 1888, the MBL has integrated education with research. In his first annual report, the founding director, C.O. Whitman, a professor from the University of Chicago, stated, "Other things being equal, the investigator is always the best instructor. The highest grade of instruction in any science can only be furnished by one who is thoroughly imbued with the scientific spirit, and who is actually engaged in original work. Whence, the propriety—and, I may say the necessity—of linking the function of instruction with that of investigation." Throughout the years, MBL has generated many breakthroughs in research and fostered many generations of scientific pioneers. MBL courses immerse students in discovery-based training side by side with the best scientists and cutting-edge equipment. The success of this approach has been revealed in surveys of discovery course alumni over the years and is exemplified by the most recent survey completed in 2016: 99% of 612 respondents (56% survey return rate) rated their MBL course experience as transformative or highly worthwhile, 96% strongly agreed or agreed with the statement "My experiences at MBL provided me with a greater appreciation of the fundamentally important research questions in this field," and 95% strongly agreed or agreed with the statement "My MBL experience helped build my confidence in my ability to learn new scientific techniques and approaches." Recently, one mentor wrote that they had sent a student to a course at Woods Hole and had received a scientist in return. This is high praise and precisely what the MBL courses set out to achieve. These achievements are pursued hand in hand with the promotion of diversity in science: in 2016, 34% of the MBL discovery course students from the United States were from underrepresented minority groups, 57% of the students were female, and 58% were foreign nationals. These are accomplishments that could be adopted by programs throughout the world.

The Educational Experience at MBL: Empowering Students to Pursue a Scientific Ideal

MBL discovery courses are often called "transformative." This is a strong statement, verified each year in formal course reviews and in the recently administered alumni survey. A "transformative experience" can be many things to many people, but it is possible to identify common, underlying educational themes at the MBL that motivate this statement, year after year. In general, students are empowered to pursue science at the very highest levels, often transforming the manner in which they approach their graduate, postdoctoral, or independent research programs. Students are given access to state-of-the-art equipment and are instructed in the use of this technology from first principles, whether in optics, biophysics, or behavior. They learn the inner workings of the equipment and the fundamental principles upon which the technology is based. Just as importantly, students work directly with outstanding faculty from around the world, day after day, pursuing novel experiments that test new ideas and foster a globe-spanning network of collaboration. From this comes a fearlessness derived from having grappled with the limitations of current technology and the boundaries of current understanding. Ultimately, students realize that they can do anything they desire scientifically as long as they seek expert guidance and as long as they are willing to delve deeply into the experiments that they want to pursue.

To fully comprehend the transformative power of the MBL, one must also look beyond the curriculum of each individual course. All of the courses exist in an intellectual summer ecosystem that extends far beyond the walls of each lab. There are numerous courses running in parallel, including those focused on neuroscience, evolution, modern cell biology, parasitology, and development. Each course is interdisciplinary and strives to bring the best scientists from around the world to work and teach at the cutting edge. Each course sponsors a seminar series, so there are outstanding guest lectures nearly every evening. Each course is a fluid, open environment, and it is not unusual for collaborations to emerge on the basis of shared interest and complementary expertise. There is an extraordinary scientific richness of unparalleled density, intensity, and collaboration.

There is more. Perhaps most importantly, all of the faculty and their assistants immerse themselves in this environment for the sole purpose of pursuing novel science and education. There are no committees or administrative distractions. Scientific conversations can linger at the café, extend to the beach during lunch, be picked up over dinner, and carry over into the late night hours. Many who have devoted time and energy to the MBL experience do so because the level of scientific engagement approaches what we had hoped for at the outset of our careers—an immersive experience surrounded by committed, enthusiastic colleagues without administrative distraction or interruption. For the students, this atmosphere is sustained for a full 4–8 weeks in the neuroscience courses discussed below. There is nothing that parallels this experience at any individual university or institute. It is an inspiring, exciting, and purposeful experience. Students and faculty leave each summer exhausted, exhilarated, and with a new sense of commitment to science.

MBL Courses and Neuroscience

The MBL provides a number of courses in neuroscience: two discovery courses, Neurobiology and Neural Systems & Behavior, and three special topics courses, Methods in Computational Neuroscience; Brains, Minds, and Machines; and the Summer Program in Neuroscience, Excellence, and Success (SPINES; formerly known as the Summer Program in Neuroscience, Ethics, and Survival). As highlighted in this article, the educational environment at the MBL fills a unique niche, producing young scientists with the passion and capacity to pursue comprehensive and rigorous neuroscience. How do the MBL programs fulfill this promise? Two areas distinguish themselves as unique to the MBL: the summer vendor equipment loan program and the recruitment of faculty and teaching assistants into a "labor of love" to train students. No single university has the capacity to achieve the faculty staffing or the laboratory equipment accessed by the vendor equipment loan program at the MBL each summer. Every summer, the program provides millions of dollars of loaned equipment (in the summer of 2016, they provided $23 million) to MBL courses and researchers. At biweekly intervals in the neuroscience discovery courses, and at more frequent intervals in special topics courses, a new set of expert faculty who are outstanding in their fields arrives. These are educational "dream teams" that are picked such that their overlapping interests and expertise create an unparalleled didactic and experimental "deep dive" into a specific sub-discipline of neuroscience. The depth of each 2 week module, combined with the breadth of the 8 week experience, is the foundation of the training in neuroscience. Because of this, the MBL courses are also ideally suited to train individuals who wish to switch disciplines. Each year, the courses include postdoctoral fellows and assistant professors who move into experimental neuroscience from other fields, including pure mathematics, physics, computer science, and engineering. By harnessing the power of cross-disciplinary research, the MBL courses are enabling this effort at the ground level.

To fully understand how the courses achieve these goals, it is necessary to describe each course in greater detail.

The goal of the Neurobiology course is to train the next generation of neuroscientists to pursue the molecular and cellular underpinnings of brain function in quantitative detail. To this end, the course has evolved over its ~40 year existence, keeping pace with the remarkable revolution in molecular biology, powerful new tools that enable the measurement and manipulation of cellular processes, and the use of diverse experimental organisms. The framework of the course is to instill the importance of quantitative approaches for dissecting how molecules control neuronal function and the experimental skills to achieve this in practice.

The present version of the Neurobiology course runs for 8 weeks and has four sections: Genomics, Electrophysiology, Imaging, and Cell Biology. Each section combines didactic lectures on the principles that guide each discipline with practical experiences that put these principles to use. For example, the Genomics section combines the most modern approaches toward the use of RNA sequencing (RNA-seq) and bioinformatics. Students participate in every aspect of data generation and analysis and emerge with a new capacity for understanding, evaluating, and working with massive genomic datasets. Electrophysiology starts with first principles of electrical circuits and amplifiers and moves to the practical application of electrophysiology for quantitative analysis of ion channels, membrane biophysics, synaptic transmission, and neural excitability. In the Imaging section, students are introduced to the fundamentals of optics, the behavior of light, and how light interacts with materials and molecules. This sets the stage for understanding the staggering advances in imaging approaches currently used in modern neuroscience. In practice, students construct and utilize advanced microscopes capable of fluorescence lifetime imaging, and multiphoton and advance light-sheet microscopy, both in vivo and ex vivo. The final section, Cell Biology, focuses entirely on intense, short-term research projects that integrate the molecular, electrophysiological, and optical tools accessed to this point. There is an emphasis on data analysis and hypothesis generation, grounded in the richness of modern cell biology. Finally, it should be emphasized that at no point do students ever pursue written laboratory exercises. All of the experiments are novel, jointly designed through the collaboration of students and faculty.

The Neural Systems & Behavior (NSB) course investigates the neural basis of behavior. Like the multidisciplinary effort of the BRAIN initiative, faculty and students hail from diverse scientific disciplines that include biology, biopsychology, engineering, mathematics, neuroethology, physics, and systems neuroscience. Over 8 weeks, each trainee is exposed to the diversity of experimental systems, each revealing unique adaptations and experimental advantages. Ultimately, each student works intensively with four different preparations, each investigated in a 2 week module under the guidance of expert faculty. The course begins by creating a common foundation in the fundamentals of electrophysiology and the analysis of dynamic neural circuitry. Although the first lessons are the principles of electronics, filters, and amplifiers, the emphasis throughout NSB is always on the analysis of how neural circuits produce behavior; students record and analyze intracellular potentials during their first evening. As the course progresses, these principles are applied to the analysis of neural systems, which have recently included rodent somatosensory cortex, rabbit cerebellum, mouse hippocampus, central neural circuitry of songbirds, weakly electric fish, zebrafish spinal motor circuitry, the crab stomatogastric ganglion, the flight system of *Drosophila melanogaster*, the *Caenorhabditis elegans* nervous system, the Cnidarian hydra, and the medicinal leech *Hirudo medicinalis*. In each case, the organism as an experimental system is carefully chosen because in combination with current technology, it is optimal for investigating a particular aspect of how neural circuits function in learning and behavior. The work is intense and creative; it is not uncommon in the course, or other MBL courses, for students to become authors on papers that include data generated as part of the courses (Thé et al., 2013; Lenschow et al., 2016).

Through this process of discovery, the students learn and harness methodologies that incorporate intracellular and extracellular electrophysiology, microfluidics, molecular genetics, single and multi-photon imaging, biomechanics, computational modeling, genomics, and bioinformatics. These technologies largely overlap with those used in Neurobiology, but in the case of NSB, the emphasis is always on how neural circuits learn and generate behavior. Consequently, trainees are encouraged to integrate, think, and make inferences across the distinct levels of biology that the individual methodologies target, spanning the spatial scales of synapses, cells, circuits, and systems and behavior and the temporal scales of neural signaling, oscillatory dynamics, gene regulation, development, and behavior. The diversity of approaches and the effort, through experimental design and technical innovation, to integrate knowledge across distinct levels of biology provides the trainees with a global, integrative perspective and training to solve problems of elucidating the biological mechanisms of the dynamic relationship between brain and behavior.

Two special topics courses in neuroscience at the MBL are Methods in Computational Neuroscience (MCN) and Brains, Minds, and Machines (BMM). MCN introduces students to the computational and mathematical techniques that are used to address how the brain solves problems at levels of neural organization ranging from single membrane channels to operations of the entire brain. In each of the first 3 weeks, the course focuses on material at increasing levels of complexity: first on modeling molecular mechanisms of ion channels; then how ion channels and pumps contribute to cellular properties and, hence, the properties of neural circuits; and finally, how neural circuits contribute to cognition and behavior. BMM uses a combination of cognitive science, neurobiology, engineering, mathematics, and computer science to build robust and sophisticated algorithms to create a more comprehensive approach toward artificial intelligence. The first half of the course focuses on the intersection between biological and computational aspects of learning and vision. The second half focuses on high-level social cognition and artificial intelligence, as well as audition, speech, and language processing. A major future goal at the

Box 1. Lessons Learned from the MBL Model of Education and Training

The power of an immersive, transformative experience: students develop a fearlessness from grappling with the latest technology and the boundaries of current understanding. There is an extraordinary scientific richness of unparalleled density, intensity, and collaboration.

- The value of hands-on mentorship: students work directly with outstanding faculty from around the world, day after day. All of the faculty and their assistants immerse themselves in this environment for the sole purpose of pursuing novel science and education. There is an extraordinary scientific richness of unparalleled density, intensity, and collaboration.
- The importance of promoting diversity: a diverse scientific workforce is essential to the success of any global effort to understand the brain because it brings new perspectives to scientific discovery and promotes teamwork across cultural, racial, and ethnic boundaries.
- Cutting-edge technologies and equipment: a unique vendor equipment loan program gives students access to the newest and most advanced scientific equipment. Together with instructors who are on the cutting edge of technology development and application, students are able to undertake experimental approaches that they may not have access to at their home institutions.
- Fostering cross-disciplinary science: MBL courses are ideally suited for training individuals moving between disciplines. Each year, the courses recruit trainees from diverse fields such as chemistry, mathematics, computer science, and engineering, and these students learn how to work together.
- Skills and networks that go beyond the lab and classroom: the hands-on experimental training is part of a larger training ecosystem including guest lectures, professional development talks, and opportunities for networking. Students and faculty return to their home institutions with renewed purpose and prepared to train others in the methodologies and approaches they have learned.

MBL will be to achieve collaboration and synergy between these two courses and the discovery courses, something that currently does not exist due to scheduling differences.

SPINES has an outstanding track record of producing successful scientists from diverse backgrounds for over 20 years. Although the pedagogical tools and the faculty have changed over the years, the goals of SPINES have remained the same: (1) to provide exposure to modern neuroscience concepts through lectures from MBL scientists about their latest research; (2) to introduce students to successful minority and women role models as faculty participating in SPINES; (3) to explore responsible conduct of research and, more generally, to learn about the ethical issues surrounding the influence of science on society; (4) to provide a laboratory experience that addresses key neuroscience knowledge and skills; (5) to teach professional career development and success skills; (6) to learn about the MBL so that students may return in another course to further enrich their careers; and (7) to provide students with a wide-ranging professional network that includes their fellow students, the faculty of SPINES, and other scientists they meet at the MBL. There are several creative approaches used in SPINES that can be adopted by others who wish to diversify the scientific workforce. Among the top are a professional development curriculum that aims to demystify success in science and academia; the recruitment of a core group of successful faculty from underrepresented groups; the incorporation of students into the SPINES "family," which includes lifelong mentoring and assistance; and the creation of cultural capital through networking with scientists and educators at the MBL.

To date, approximately 400 graduate students, postdoctoral fellows, and junior faculty have come to the MBL to participate in SPINES. Alumni have gone on to publish in top journals in the field; have been successful at obtaining competitive grants from NIH, NSF, and research foundations; have been selected for special scientific accolades (including HHMI investigator); and have become leaders in their respective fields. Beyond the numbers, some of the best evidence of success is comments from students who regularly refer to the course as transformative and among the most significant experiences in their professional lives. It is empowering for trainees to meet successful role models from underrepresented groups at SPINES and to receive lifelong mentoring as a part of the SPINES family. And SPINES alumni regularly return to the MBL to participate in one or more of the other neuroscience discovery courses.

Conclusions

In conclusion, MBL courses are a fertile training ground for the neuroscience of the new millennium. These courses foster cross-disciplinary training, combining extraordinary depth and breadth with access to the most important existing and emerging technologies (Box 1). In essence, as an educational force, the courses ensure that the frontiers of brain research will be continually pushed forward by future generations of highly qualified, interconnected young neuroscientists. It is extremely important that this training is directed across cultural, racial, gender, and ethnic boundaries. Without question, the nature of the questions we pose and the answers we discover in neuroscience will be strongly shaped by the ethnic, racial, cultural, and gender-based composition of the scientific workforce. A diverse scientific workforce is essential to the success of any global effort to understand the brain.

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Fund Director of the Division of Education at the Marine Biological Laboratory in Woods Hole, MA. Prior to arriving at MBL, she was at the University of Vermont, where she was Professor of Neurological Sciences, the founding director of the university-wide Neuroscience Graduate Program, and Director of the Transdisciplinary Research Initiative in Neuroscience, Behavior, and Health. She was also co-director of the MBL Neurobiology course from 2004 to 2007. Keith Trujillo was co-director of SPINES from 2010 to 2016, Jean King was co-director of SPINES from 2012 to 2016, and Edward Castaneda has been co-director of SPINES from 2015 to the present. Graeme Davis was a co-director of Neurobiology from 2010 to 2016, Timothy Ryan was a co-director of Neurobiology from 2012 to 2016, and André Fenton and Hans Hofmann have been co-directors of Neural Systems & Behavior from 2013 to the present.

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