



BME 2.0 AT JOHNS HOPKINS

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With the invention of transformative technologies such as the computer and GPS navigation, the 20th century brought remarkable progress in our ability to map and control the external world. In the 21st century, the focus has shifted to mapping and controlling the internal world, ushering in a Biomedical Age of technological breakthroughs for sensing and manipulating the molecules, cells, tissues, and organs that make up the human body. This explosion of technology is leading to new frontiers in biomedical discovery, data science, biomanufacturing, and translational research—we are now Engineering the Future of Medicine. Now, the educational system must evolve to prepare the next generation of engineers to adapt to and lead in this new age of biomedical discovery and innovation. This article briefly reviews our history of academics at Johns Hopkins and introduces BME 2.0, which we believe will be the next wave of biomedical engineering education for the Biomedical Age.¹

The central core of the Johns Hopkins BME 2.0 education is a curriculum that provides every student with the training necessary to lead in the Biomedical Age of the 21st century. The core principles of the BME 2.0 undergraduate education are:

- Teaching students through practice, providing opportunities to engage with faculty and solve real biomedical and engineering problems, starting on day one;
- Training all students to be bilingual in the scientific languages of modern molecular biology and computational and analytical modeling of complex biological systems;
- Ensuring that every student is fluent in biomedical data science;
- Giving every student the opportunity to pursue research and design experiences;
- Emphasizing flexibility through project-based courses in specialized focus areas so that all students can pursue their own path in one of the emerging disciplines of biomedical data science, computational medicine, genomics and systems biology, imaging and medical devices, immunoengineering, neuroengineering, and translational cell and tissue engineering.

Ground Zero: The Early Years

BME as a discipline emerged in the 1960s and 1970s, led by several co-founding departments at Johns Hopkins, Case Western, the University of Pennsylvania, the University of Rochester, Rensselaer Polytechnic Institute, and Duke.² BME at Johns Hopkins was first established as a sub-department within the Department of Medicine, and holds the longest-running training grant for BME PhD education, founded c.

¹ BME 2.0 was [announced](#) October 12, 2017 at BMES.

² https://ethw.org/Oral-History:Richard_J._Johns

1961, in the nation.

The first degree-granting undergraduate curriculum in biomedical engineering at Johns Hopkins, what we term “ground-zero,” was founded in 1979, and was largely organized as an outgrowth of the traditional engineering disciplines of chemical engineering (ChE), electrical engineering (EE), materials science (MS), and mechanical engineering (ME). In the early years of the undergraduate program at JHU, students would declare an area of concentration in ChE, EE, MS, or ME; students interested in studying neurons or the pacing of the heart would likely choose focus area concentrations in EE, whereas those interested in biomaterials often selected MS or ChE. Classes in these concentration areas were supplemented with two Physiological Foundations courses, a common denominator for all BME undergraduates at JHU, which provided an in-depth education in physiology from a quantitative and engineering perspective. Figure 1 depicts the evolution of Hopkins BME over the past 50+ years.

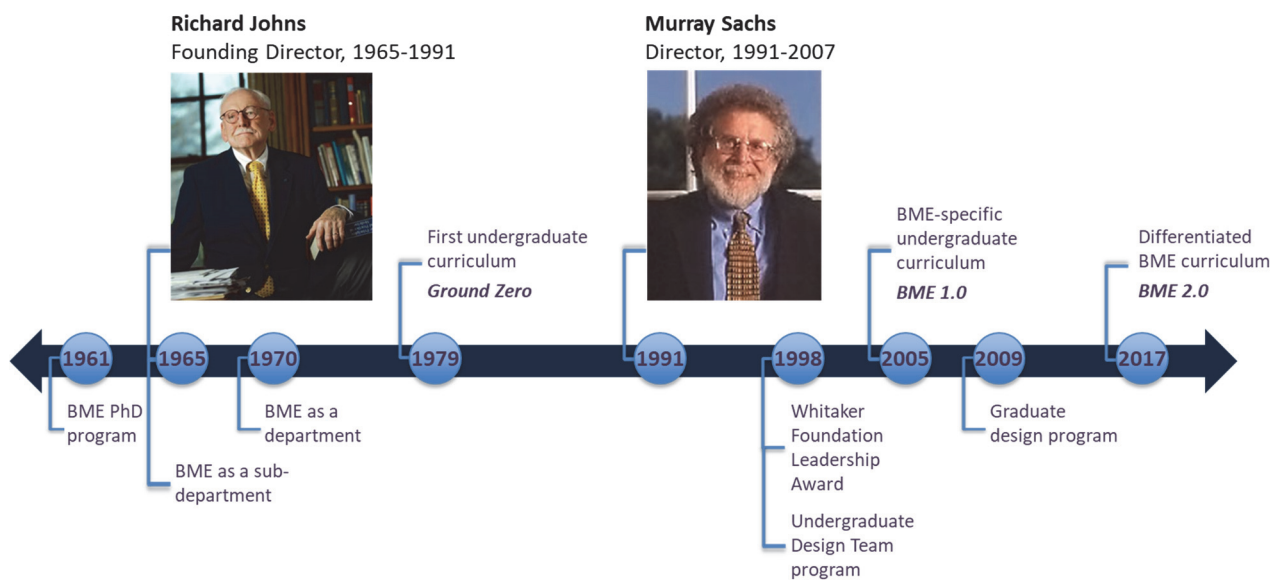


Figure 1: A timeline depicting the history of biomedical engineering at Johns Hopkins. Biomedical engineering originated in the 1960s as graduate programs at Johns Hopkins University, University of Pennsylvania, University of Rochester, Duke University, and others. Johns Hopkins launched its first biomedical engineering undergraduate program in 1979. Under the direction of Murray Sachs, Johns Hopkins engineering faculty developed BME 1.0, the first BME-specific undergraduate curriculum, with support from a 1998 Whitaker Foundation Leadership award. Artin Shoukas, Robert Allen, and their Hopkins BME colleagues introduced multi-generational design teams in 2001. Bessie Darling Massey Professor and Director Michael I. Miller announced the launch of BME 2.0 at the 2017 Biomedical Engineering Society annual meeting.

BME 1.0 and the Transition to BME 2.0

A core of classical engineering classes, combined with quantitative physiology, formed the basis of almost all of the BME curricula³ throughout the 20th century, but this model became insufficient as the field matured. The fact that BME is a truly interdisciplinary integration of biochemical, electrical, and mechanical systems was already appreciated during the 1970s. Richard Johns, the founding director of Johns Hopkins BME, articulated the idea of BME as a system-of-biosystems in his *Systems Biology*

³ Similarities and Differences in Biomedical Engineering Undergraduate Curricula in the United States, Gatchell and Linsenmeir, 121st ASEE Annual Conference and Exposition, PaperID#9731, ASEE, 2014.

whitepaper to the National Institutes of Health, likely one of the earliest uses of the term. Johns Hopkins faculty recognized the need for a BME-specific curriculum and, supported by a 1998 Whitaker Foundation Leadership Award, finalized “BME 1.0,” a fully integrated engineering curriculum based on the biomedical sciences in 2005.⁴ The Whitaker award funded the building of Clark Hall, which became home to the first biomedical engineering faculty in the School of Engineering at the Homewood Campus.⁵ As part of the BME 1.0 curriculum, these faculty taught core engineering principles from the perspective of biomedicine, and biomedicine from the perspective of engineering, through a set of courses that includes Molecules and Cells; Models and Simulations; Signals, Systems and Controls; Statistical Mechanics and Thermodynamics; and Systems Bioengineering I-III, with specific emphasis on the cardiovascular system, the nervous system, and cellular and molecular biology, respectively.

BME 2.0: A Differentiated Curriculum with Core Disciplines

The explosion of biomedical technology at the dawn of the 21st century has drastically changed both what we teach and how we teach it. The rapid growth in our ability to acquire and analyze information has accelerated the advancement of computational digital tools, launching an age of Big Data characterized by the ubiquitous deployment of sensors. At the same time, technologies for 3D printing⁶ are enabling engineers to manufacture everything from device prototypes to human tissues and organs. These advances are shifting the economics of biomedical solutions, making it possible to offer advanced, state-of-the-art technologies to students at all levels of our educational mission. Undergraduates are able to conduct their own research and design projects, applying their skills and knowledge at the highest levels: *learning, doing, and teaching*. With the prevalence of sophisticated technologies, combined with rapid advances in artificial intelligence and machine learning, we are primed to develop a second-generation curriculum to train a new wave of data-driven biomedical engineers.⁷

Towards this end, we have launched “BME 2.0,” a new BME curriculum that translates the latest research breakthroughs into the undergraduate education. The BME 2.0 curriculum is organized into seven focus areas (see below), each built upon the major discoveries in a modern discipline at the forefront of biomedical research. These focus areas represent the research strengths of Hopkins BME faculty, and align with the biomedical engineering disciplines defined by *Nature Biomedical Engineering* (see Figure 2). The BME 2.0 focus areas allow students at the undergraduate level to gain a depth of knowledge in advanced disciplines that is traditionally accessible only at the graduate level. *Through these focus areas, BME 2.0 is our first curriculum to provide students the flexibility in their junior and senior years to personalize their education according to their interests and career goals.*

The focus areas for Johns Hopkins BME are:

- **Biomedical Data Science:** Extracting knowledge from biomedical datasets of all sizes to understand and solve health-related problems
- **Computational Medicine:** Generating solutions in personalized medicine by building and utilizing computational models of health and disease
- **Genomics and Systems Biology:** Creating tools to understand the multi-scaled genetic,

⁴ https://www.eurekalert.org/pub_releases/1998-10/WF-WMLI-141098.php

⁵ <https://pages.jh.edu/~gazette/2001/aug0601/06clark.html>

⁶ <https://www.economist.com/leaders/2012/04/21/the-third-industrial-revolution>

⁷ <https://engineering.virginia.edu/news/2019/10/op-ed-times-higher-education-we-must-build-data-driven-generation-biomedical-engineers>

epigenetic, molecular, and cellular components of disease

- **Imaging and Medical Devices:** Building new medical devices and imaging technologies to improve disease diagnosis and guide clinical procedures
- **Immunoengineering:** Harnessing the power of the immune system to treat diseases such as cancer and promote tissue regeneration for improved healing and repair
- **Neuroengineering:** Applying innovative experimental and data-driven approaches to understand, diagnose, and treat disorders of the brain
- **Translational Cell and Tissue Engineering:** Developing and translating advanced technologies to enhance or restore function at the molecular, cellular, and tissue levels

Artificial organs		Computational medicine	10	Molecular and cell engineering	8
Bio-MEMS		Diagnostics	1	Nanomedicine	2
Biochips		Drug and cell delivery	3	Neural engineering	9
Bioelectronics		Genetic engineering	4	Orthopaedics	3
Biomaterials	4	Genomic engineering	4	Precision medicine	7
Biomechanics	1	Health informatics	1	Prosthetics	2
Biomedical analytics	4	Health systems engineering		Regenerative medicine	5
Biomedical imaging	11	Human modelling and simulation	4	Rehabilitation engineering	1
Biomedical instrumentation	5	Immunoengineering	5	Synthetic biology	3
Biomedical sensors	2	Implants	1	Systems biology	8
Biomolecular engineering	4	Mechanobiology	2	Systems physiology	9
Bionics		Medical devices	4	Tissue engineering	5
Biosignal processing	2	Medical robotics	1	Translational medicine	9
Clinical engineering	1	Medical technology	5	Vaccines	1
Clinical trials	1	Micro- and nanobiotechnology	2	Wearable technology	

Figure 2. Biomedical engineering research topics defined by *Nature Biomedical Engineering*; the number of primary Hopkins BME faculty in each area is noted.

BME 2.0: Vertically Integrated via Multi-Generational Learning

A key principle of BME 2.0 is that students are practicing engineers from day one. More than two decades ago, Hopkins BME faculty pioneered the multi-generation design team model⁸ that mirrors the vertically integrated teaching philosophy of medical schools, which brings students, interns, residents, and faculty together in teams practicing the *learn one - do one - teach one* model. Based on the success of our undergraduate Design Team program, we have applied this strategy to the BME 2.0 undergraduate curriculum, creating a vertically integrated program characterized by a diverse and multi-generational

⁸ J. Rice, R. Allen, and A. Shoukas, 2001. Longitudinal Design Teams: Students Teaching Students. American Society of Mechanical Engineering, Design Engineering Division, pages 85-92.

learning environment. Alongside our faculty experts and clinical collaborators, students work in small teams on real-world projects with basic science and translational impact. These teams, composed of freshmen, sophomores, juniors, and seniors, solve engineering and healthcare problems while *practicing* the discipline through project-based courses: sequencing a genome, computationally engineering a stem cell, designing a synthetic human chromosome, building an imaging system, genetically modifying cells, applying big data to engineer better approaches to healthcare, and more.

The Core of BME 2.0: Reflecting the Future

The BME 2.0 curriculum was designed to provide students with both depth and breadth of learning: while the seven focus areas offer specialized and individualized learning (depth), a core curriculum teaches the fundamentals of engineering, math, and the life and basic sciences (breadth). The pyramid shown in Figure 3 describes the core set of computational and biomedical learning required to understand physiological processes related to the focus areas from a quantitative perspective.

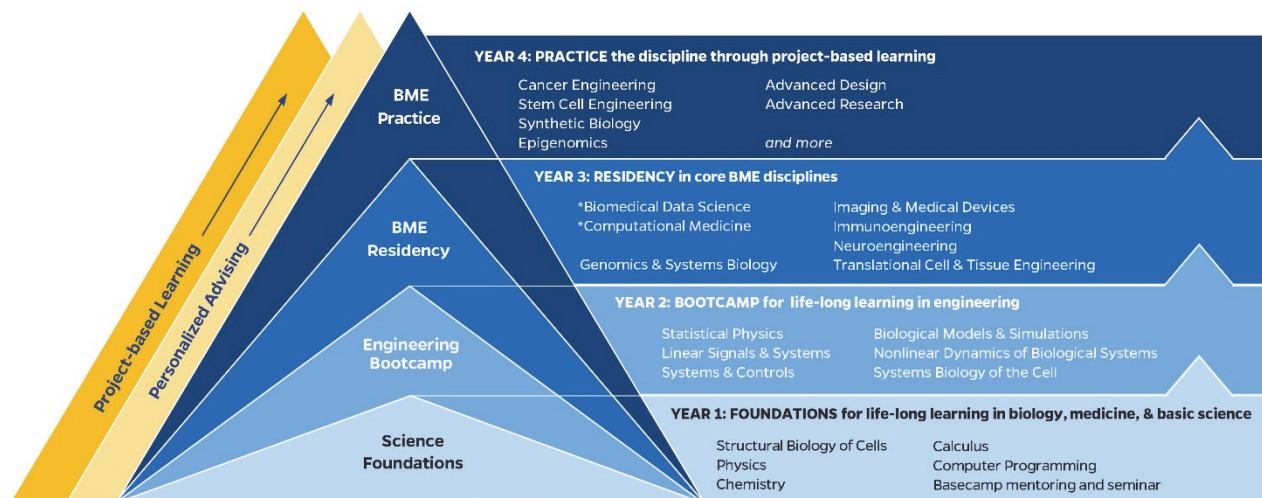


Figure 3: The BME 2.0 curriculum follows a vertically integrating pyramid structure in which all educational components continue throughout the remaining years. BME 2.0 begins with a foundation of quantitative life science training (Foundations and Bootcamp), followed by two years of advanced BME practice in one of seven advanced focus areas (Residency and Practice). All four years feature project-based learning, clinical immersion, research, and design, with multiple opportunities for translation. Throughout the BME 2.0 experience, students benefit from career exploration and personalized advising programs, receiving individualized guidance and support from a faculty expert in their chosen focus area.

The BME 2.0 core curriculum (see Figure 4) begins with an in-depth introduction to modern life sciences and other basic science foundations in the first year (Science Foundations), followed by rigorous training in the quantitative and analytical sciences during the second year (BME Bootcamp). During the junior and senior years (BME Residency and BME Practice, respectively), students have the freedom to explore their areas of interest as they differentiate into their chosen focus areas.

The core curriculum, designed to provide the foundations needed for advanced focus area learning, is:

- **Science Foundations:** Students gain a breadth of knowledge in the STEM disciplines—physics, chemistry, mathematics, programming, biology, and the life sciences—and learn the principles of experimentation and design, starting on day one. First-year students are exposed to BME faculty, research, and other opportunities to enhance their learning and growth during the Basecamp

mentoring program, part of our new “Structural Biology of Cells” course, and Basecamp seminar series.

- **BME Bootcamp:** Students apply analytical approaches to model and engineer biological systems at the molecular, cellular, and organ levels through a series of eight-week courses in statistical physics, signals and linear and nonlinear systems, controls, modeling and simulation, and systems biology of the cell.
- **BME Residency:** Students specialize in cutting-edge BME disciplines through half-semester focus area core courses based on our pioneering research. All students learn to answer questions of health and disease using complex biomedical datasets through required courses in computational cardiology and biomedical data science.
- **BME Practice:** Students put knowledge into practice through project-based courses, design projects, and advanced research in their specialized focus areas.

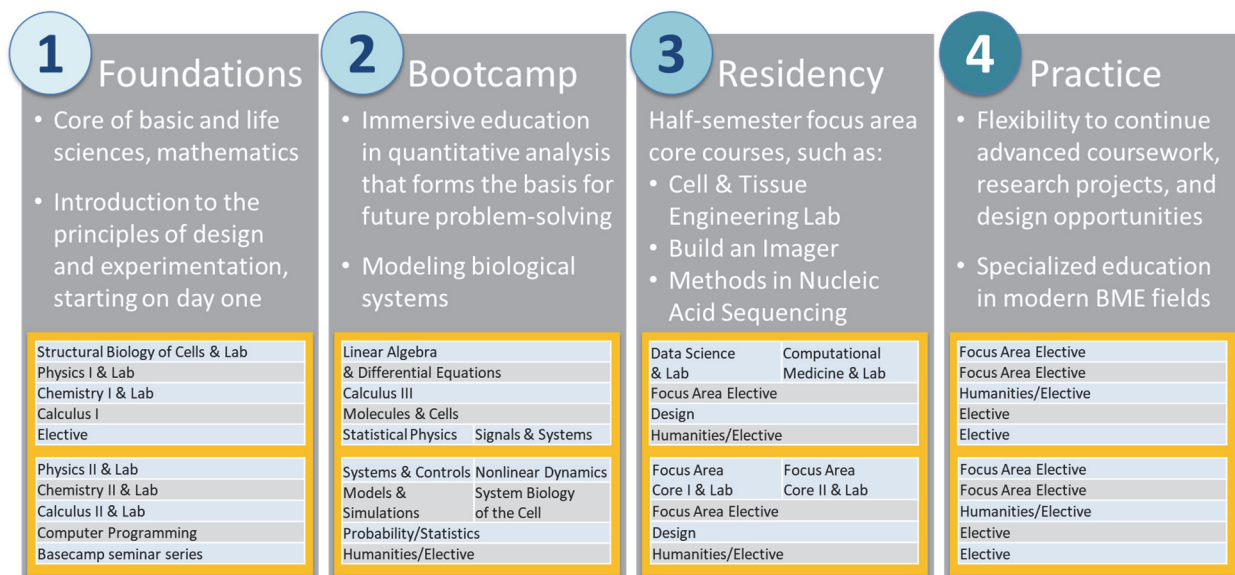


Figure 4: A sample four-year BME 2.0 curriculum.

BME 2.0 Focus Areas and Industry

As we developed our focus area-based curriculum, our goal was to reflect the latest developments in the biomedical industry and marketplace, including the biotechnology, pharmaceutical, and medical technology sectors. For this, we have developed a sequence of classes that translate easily to the industries that are hiring our students. A few examples by focus area include:

- **Biomedical Data Science:** *Advanced Data Science for Biomedical Engineering, Biomedical Data Science*
- **Computational Medicine:** *Precision Care Medicine I & 2, Computational Medicine: Cardiology, Introduction to Computational Medicine*
- **Genomics and Systems Biology:** *Methods in Nucleic Acid Sequencing, Computational Genomics: Data Analysis, Foundations of Computational Biology and Bioinformatics, Computational Stem Cell Biology, Epigenetics at the Crossroads of Genes and the Environment*

- **Imaging and Medical Devices:** *Build an Imager, Medical Imaging Systems, Imaging Instrumentation, Principles of the Design of Biomedical Instrumentation*
- **Immunoengineering:** *Molecular Immunoengineering*
- **Neuroengineering:** *Neuro Data Design, Models of the Neuron, Rehabilitation Engineering and Design Lab*
- **Translational Cell and Tissue Engineering:** *Cell and Tissue Engineering Lab, Cellular Engineering, Tissue Engineering*

As the creation of engineered biomedical tools dramatically accelerates, and technologies move faster and faster from first discovery to global use and clinical application, now is the right time to introduce this concept of a differentiated curriculum. We must take advantage of the widespread availability and affordability of advanced scientific tools and provide our students with access to real-world project applications relevant to their future careers. This next generation of differentiated curriculum, based on specialized focus areas and project-based learning, demonstrates to employers the value that a biomedical engineering graduate can bring to their company. *With BME 2.0, students at Johns Hopkins are trained in the technologies of the marketplace, fluent in both the life science and quantitative disciplines.*

Conclusion

In its 50 years of existence, biomedical engineering has had profound scientific and societal impact, changing the nature of biological research and medical practice. We are poised to redefine the discipline once again, modernizing the way we train biomedical engineers for tomorrow. This transition emphasizes both breadth and depth of learning to prepare students for the demands of biomedical industry. The first two years of the BME 2.0 curriculum focus on foundational learning in engineering and the life sciences—teaching biology from a quantitative perspective, and teaching engineering from the perspective of life science applications. During the final two years, students build depth in the specialized areas of biomedical engineering that have emerged over the past several decades, and put their knowledge into practice through project-based learning. Throughout the BME 2.0 experience, students gain key skills such as problem-solving and working as a team, and learn self-motivation through the personalized design of their own curriculum. These principles of BME 2.0 will empower the next generation to Engineer the Future of Medicine.