Computational Medicine (CM) is an emerging discipline devoted to the development of quantitative approaches for understanding the mechanisms, diagnosis and treatment of human disease through applications of mathematics, engineering and computational science. The core approach of CM is to develop computational models of the molecular biology, physiology, and anatomy of disease, and apply these models to improve patient care. CM approaches can provide insight into and across many areas of biology, including genetics, genomics, molecular networks, cellular and tissue physiology, organ systems, and whole body pharmacology.

CM research at ICM is sub-divided into four key areas: Computational Molecular Medicine (http://icm.jhu.edu/research-areas-2/computational-molecular-medicine); Computational Physiological Medicine (http://icm.jhu.edu/research-areas-2/computational-physiological-medicine); Computational Anatomy (http://icm.jhu.edu/research-areas-2/computational-anatomy); Computational Healthcare (http://icm.jhu.edu/research-areas-2/computational-healthcare). Techniques for and applications in each of these four key subareas are introduced during the required core courses, exposing students to the breadth of Computational Medicine, and enabling each student to identify a preferred area of interest:

- **Computational Physiological Medicine** develops mechanistic models of biological systems in disease, and applies the insights gained from these models to develop improved diagnostics and therapies. Therapies could be diverse drugs, electrical stimulation, mechanical support devices and more.

- **Computational Molecular Medicine** harnesses the enormous amount of disease-relevant data produced by next-generation sequencing, microarray and proteomic experiments of large patient cohorts, using statistical models to identify the drivers of disease and the susceptible links in disease networks.

- **Computational Anatomy** uses medical imaging to analyze the variation in structure of human organs in health and disease. Such image analysis has been integrated into clinical workflows to assist in the diagnosis and prognosis of complex diseases.

- **Computational Healthcare** is an emerging field devoted to understanding populations of patients and their interaction with all aspects of the healthcare process.

CM is distinct from Computational Biology in its focus on human health, disease, and treatment; translation to and application in the clinic is a near-term goal of all CM research. Applications of CM are as broad as medicine itself, and include: identification of optimal drugs using associated genomic and proteomic biomarkers; discovery of image-based biomarkers for diagnosis and prognosis; design and dynamic adjustment of individualized non-drug therapies such as deep brain stimulation, cardiac stimulation, and cochlear implants; modeling and learning from patient EHR data to improve patient outcomes and efficiency of care; optimization of healthcare policy decisions by quantitative analysis; and more. CM is one of the pillars of the University’s Strategic Initiative in Individualized Health.

**Computational Medicine Minor**
The Institute for Computational Medicine (ICM) is proud to offer an undergraduate minor in Computational Medicine, the first educational program in CM, reflecting Johns Hopkins University’s leadership in this field. Like the ICM itself, the undergraduate minor in Computational Medicine is integrative and multidisciplinary. The 18 ICM Core Faculty who serve as advisors to the undergraduate minor hold primary and joint appointments in multiple Johns Hopkins University departments and schools including Biomedical Engineering, Computer Science, Electrical and Computer Engineering, Mechanical Engineering, Applied Mathematics and Statistics (WSE); Neurosurgery, Emergency Medicine, Medicine, and the Divisions of Cardiology and Health Sciences Informatics (SOM); and Health Policy and Management (BSPH).

With a minor in CM, undergraduates will have a solid grounding in the development and application of computational methods in multiple key areas of medicine. Specifically, undergraduates will understand how mathematical models can be constructed from biophysical laws or experimental data, and how predictions from these models facilitate diagnosis and treatment of a disease. Undergraduates will become conversant with a wide variety of statistical, deterministic and stochastic modeling methods, skills that are essential to the advancement of modern medicine, and are prized both in academic research and industrial research.

**Minor Prerequisites**
Before attempting the minor, undergraduates will have taken the following courses. For a course to count towards the minor, a minimum grade of C- is required (courses graded as ‘S/U’ do not satisfy prerequisites):

1. Calculus I
2. Calculus II
3. Probability and Statistics: either a single course covering both (e.g. EN.553.310 or EN.553.311) or a course devoted to each (e.g., EN.553.420 and EN.553.430) – this may be taken concurrent with core course EN.580.431
4. At least one (1) additional course in mathematics or applied mathematics (at least 3 credits)
5. At least one (1) of the following computer programming course (at least 3 credits): EN.500.112, EN.580.200, EN.601.120
6. At least one (1) biological sciences course at the 200 level or higher (at least 3 credits). AP Biology credits do not satisfy this requirement.

**Core Courses**
The required core courses for the minor are Introduction to Computational Medicine I (EN.580.431) and one of the following:

- Computational Molecular Medicine (EN.553.450) or
- Foundations of Computational Biology and Bioinformatics II (EN.580.488).

EN.580.431 covers computational anatomy and physiology and will be jointly taught by ICM faculty from multiple departments.

EN.550.450 focuses on molecular medicine and computational healthcare while EN.580.488 introduces probabilistic modeling and information theory applied to biological sequence analysis. Both courses require background in probability theory and statistics.

Core courses may not be taken concurrently.

**Distinguished Seminar Series**
Students enrolled in the Computational Medicine Minor are **REQUIRED** to attend 6 ICM Distinguished Seminars (https://icm.jhu.edu/seminar-series) in person by graduation. Documentation
of seminar attendance is two-fold. For each seminar attended, students must: (1) sign-in at the seminar and (2) complete an online Seminar Attendance Form (https://docs.google.com/forms/d/e/1FAIpQLSdBzF2XW6bPTNRygs92EIkfys3xfkcM3hphdU868yDnAzaDoQ/viewform).

Elective Courses
Following satisfaction of the prerequisites, to complete the minor undergraduates must take at least 18 credits of CM courses. This includes two one-semester core courses plus approved elective courses selected from those listed below. The following restrictions are noted:

1. No more than 3 of the 18 elective credits may consist of independent research in computational medicine or approved CM-related research. Eligibility of independent research as "M", "C", or "MC", or neither is at the advisor's discretion. Note: The Senior Design Project Course (EN.580.580/581) may count toward independent research, provided that the research falls within the field of computational medicine, as decided by the advisor;
2. The 18 credits will all be at 300-level or above, and courses must be passed at a C- level or above;
3. At least 1 non-core/elective course must be outside student's home department;
4. At least 2 non-core/elective courses must have a substantial biology or medicine component, as identified in the list below with an "M" designation;
5. At least 1 non-core course must have a significant component of "applied programming" (distinct from a course on computer language or on programming such as Intermediate Computer Programming in Computer Science) to satisfy the computational component, as identified in the list of electives with an "C" designation;
6. All courses must be passed at a C- level or above;
7. A class may not be counted as both a prerequisite and an elective.

Students may suggest elective courses to be added to the list by completing a "Class Approval Request Form". Requests should be made to Alecia Flynn (aflynn12@jhu.edu) and will be reviewed by the CM Minor Curriculum Committee.

Electrical and Computer Engineering

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.520.315</td>
<td>Intro. to Bio-Inspired Processing of Audio-Visual Signals</td>
<td>3</td>
</tr>
<tr>
<td>EN.520.432</td>
<td>Medical Imaging Systems (M)</td>
<td>3</td>
</tr>
<tr>
<td>EN.520.601</td>
<td>Introduction to Linear Systems Theory</td>
<td>3</td>
</tr>
<tr>
<td>EN.520.621</td>
<td>Introduction To Nonlinear Systems</td>
<td>3</td>
</tr>
<tr>
<td>EN.520.473</td>
<td>Magnetic Resonance in Medicine (MC)</td>
<td>3</td>
</tr>
</tbody>
</table>

Mechanical Engineering

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.530.343</td>
<td>Design and Analysis of Dynamical Systems</td>
<td>3</td>
</tr>
<tr>
<td>EN.530.676</td>
<td>Locomotion II: Dynamics (M)</td>
<td>3</td>
</tr>
</tbody>
</table>

Chemical and Biomedical Engineering

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.540.400</td>
<td>Project in Design: Pharmacokinetics (MC)</td>
<td>3</td>
</tr>
<tr>
<td>EN.540.409</td>
<td>Dynamic Modeling and Control (C)</td>
<td>4</td>
</tr>
<tr>
<td>EN.540.421</td>
<td>Project in Design: Pharmacodynamics (MC)</td>
<td>3</td>
</tr>
<tr>
<td>EN.540.638</td>
<td>Advanced Topics in Pharmacokinetics and Pharmacodynamics I (C)</td>
<td>3</td>
</tr>
</tbody>
</table>

Applied Mathematics and Statistics

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.553.391</td>
<td>Dynamical Systems</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.420</td>
<td>Introduction to Probability</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.426</td>
<td>Introduction to Stochastic Processes</td>
<td>4</td>
</tr>
</tbody>
</table>

Biomedical Engineering

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.580.420</td>
<td>Build-a-Genome (M)</td>
<td>4</td>
</tr>
<tr>
<td>EN.580.492</td>
<td>Build-a-Genome Mentor (M)</td>
<td>4</td>
</tr>
<tr>
<td>EN.580.430</td>
<td>Systems Pharmacology and Personalized Medicine (MC)</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.445</td>
<td>Networks (C)</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.460</td>
<td>Theory of Cancer (MC)</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.462</td>
<td>Representations of Choice (MC)</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.468</td>
<td>The Art of Data Science (C)</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.488</td>
<td>Foundations of Computational Biology and Bioinformatics II (MC)</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.491</td>
<td>Learning Theory (C)</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.689</td>
<td>Computational Personal Genomics (MC)</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.694</td>
<td>Statistical Connectomics (MC)</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.446</td>
<td>Physical Epigenetics (M)</td>
<td>3</td>
</tr>
</tbody>
</table>

Computer Science

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.601.350</td>
<td>Introduction to Genomic Research (MC)</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.448</td>
<td>Computational Genomics: Data Analysis (MC)</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.447</td>
<td>Computational Genomics: Sequences (MC)</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.455</td>
<td>Computer Integrated Surgery I (C)</td>
<td>4</td>
</tr>
<tr>
<td>EN.601.461</td>
<td>Computer Vision (C)</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.475</td>
<td>Machine Learning (C)</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.476</td>
<td>Machine Learning: Data to Models (C)</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.482</td>
<td>Machine Learning: Deep Learning (C)</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.485</td>
<td>Probabilistic Models of the Visual Cortex (C)</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.723</td>
<td>Advanced Topics in Data-Intensive Computing (C)</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.750</td>
<td>Frontiers of Sequencing Data Analysis (MC)</td>
<td>3</td>
</tr>
<tr>
<td>AS.250.353</td>
<td>Computational Biology</td>
<td>3</td>
</tr>
</tbody>
</table>

Declaring the Minor

Interested students should contact Alecia Flynn, Sr. Academic Coordinator, to receive guidance on declaring the minor:

Phone: 410-516-6892
Email: aflynn12@jhu.edu

Specific questions regarding the minor requirements and courses can be directed to Dr. Joshua Vogelstein (jovo@jhu.edu), Director of Undergraduate Studies for the CM minor.

BME MSE Computational Medicine (CM) Focus Area

The Department of Biomedical Engineering (https://www.bme.jhu.edu) offers a Focus Area in Computational Medicine (BME MSE CM Focus Area) as part of its Masters of Science and Engineering program (https://www.bme.jhu.edu/graduate/mse/overview). The BME MSE CM Focus Area is a course-based degree program comprising two BME core competency courses, three CM focus area courses, three CM focus area electives, and at least two electives outside the program. In addition to these 10 courses, students are also required to complete the Distinguished Seminar Series in Computational Medicine course. Required CM courses and focus area electives are taught by core
To Apply

Perspective students should apply to the MSE program in the Department of Biomedical Engineering (https://www.bme.jhu.edu/graduate/mse/apply), indicating an interest in Computational Medicine.

BME MSE CM Focus Area Curriculum Requirements
Core Biomedical Engineering Competency
All BME Department MSE students are expected to complete two of the following courses:

- Systems Bioengineering 1 (EN.580.721)
- Systems Bioengineering 2 (EN.580.722)
- Systems Bioengineering 3 (EN.580.779)

Required CM Focus Area Courses
Two of the following courses:

- Introduction to Computational Medicine I (EN.580.631)
- Choose either:
  - Foundations of Computational Biology & Bioinformatics II (EN.580.688)
  - Computational Molecular Medicine (EN.553.650)

CM Focus Area Electives
CM students will complete additional electives selected from the following list (choose at least three of these courses):

- Principles of Complex Networked Systems (EN.520.622)
- Advanced Topics in Pharmacokinetics and Pharmacodynamics (EN.540.639)
- Introduction to Probability (EN.553.620)
- Introduction to Stochastic Processes (EN.553.426/626)
- Modeling, Simulation, and Monte Carlo (EN.553.664)
- Models of the Neuron (EN.580.639)
- Systems Pharmacology & Personalized Medicine (EN.580.640)
- Precision Care Design I & II (EN.580.670/671)
- Computational Stem Cell Biology (EN.580.647)
- Neuro Data Design (EN.580.697/698)
- Practical Ethics for Future Leaders (EN.580.496)
- Advanced Topics in Genomic Data Analysis (EN.601.641)
- Computational Genomics: Data Analysis (EN.601.638)
- Machine Learning (EN.601.675)
- Machine Learning: Data to Models (EN.601.676)

Additional Electives
Students will select additional graduate level science, technology, engineering, or math courses with the consent of their advisor to complete the total of 10 full courses required for graduation.

The Pre-Doctoral Training Program in Computational Medicine

The Pre-Doctoral Training Program in Computational Medicine, funded by the National Institute of General Medical Sciences, supports selected trainees from the departments of Biomedical Engineering and Applied Mathematics & Statistics.

Students chosen for this Ruth L. Kirschstein National Research Service Award institutional training grant will learn through a combination of focused coursework and dissertation research alongside computational medicine training program faculty mentors from across the Johns Hopkins Whiting School of Engineering and the School of Medicine. The program is designed to prepare graduates to fill the growing need for researchers trained in computational medicine in both industry and academia.

Trainees will be part of an exceptional and distinctive community of students and faculty exploring the possibilities of computational medicine. Trainees will learn how to develop models of biological systems in health and disease, constrain these models using data collected from patients, and apply models to deliver improved diagnoses and therapies.

To Apply

Prospective trainees should apply to the PhD programs of the Departments of Biomedical Engineering (https://www.bme.jhu.edu/graduate/phd/apply) or Applied Mathematics and Statistics (https://engineering.jhu.edu/ams/graduate-studies/admissions-criteria-admission-process), indicating an interest in pursuing pre-doctoral training in Computational Medicine.

Program Milestones
Year One

By the end of the first year, trainees will complete the following:

- Introduction to Computational Medicine I (EN.580.631)
- Foundations of Computational Biology & Bioinformatics II (EN.580.688) or Computational Molecular Medicine (EN.553.650)
- Required home department course work
- At least one CM research rotation in a laboratory of participating Program Faculty

Year Two

By the end of the second year, trainees will complete:

- One clinical rotation in the laboratory of a clinician-researcher who works with patient data
- Graduate Board Oral (GBO) examination

Year Three and Beyond

- Doctoral Board Oral (DBO) examination (30 months from matriculation)
- Participate in planning periodic Computational Medicine conference (optional)
- Thesis Defense (60 months from matriculation)

Additional Requirements

Each year in the program, trainees will attend the CM Journal Club, the Distinguished Seminars in Computational Medicine, and the annual ICM Retreat.

Faculty

Director

Raimond Winslow
Director of The Institute for Computational Medicine, Director of The Pre-Doctoral Training Program in Computational Medicine, Raj and Neera Singh Professor of Biomedical Engineering

Associate Director, Institute for Computational Medicine

Sridevi Sarma
Associate Professor, Dept. of Biomedical Engineering
Co-Director, Pre-Doctoral Training Program
Feilim Mac Gabhann
Associate Professor, Dept. of Biomedical Engineering

Core Faculty
William S. Anderson
Associate Professor, Dept. of Neurosurgery, Attending Neurosurgeon at
The Johns Hopkins Hospital

Joel Bader
Professor, Dept. of Biomedical Engineering, Bioinformatics and
Computational Biology Lab

Patrick Boyle
Assistant Research Professor, Dept. of Biomedical Engineering

Nicolas Charon
Assistant Professor, Dept. of Applied Mathematics and Statistics, Center
for Imaging Sciences

Nathan Crone
Professor, Dept. of Neurology

Donald Geman
Professor, Applied Mathematics and Statistics, Center for Imaging
Sciences

Rachel Karchin
Associate Professor, Dept. of Biomedical Engineering, The William R.
Brody Faculty Scholar

Michael I. Miller
Herschel and Ruth Seder Professor, Dept. of Biomedical Engineering,
Director of Center for Imaging Sciences

Rajat Mittal
Professor, Dept. of Mechanical Engineering

Tilak Ratnanather
Associate Research Professor, Dept. of Biomedical Engineering

Suchi Saria
Assistant Professor, Dept. of Computer Science

Natalia Trayanova
Murray B. Sachs Professor, Dept. of Biomedical Engineering

Rene Vidal
Professor, Dept. of Biomedical Engineering, Computer Science,
Mechanical Engineering, and Electrical and Computer Engineering,
Director of Vision Dynamics and Learning Lab

Joshua Vogelstein
Assistant Professor, Dept. of Biomedical Engineering

Laurent Younes
Professor and Chair, Dept. of Applied Mathematics and Statistics