CENTER FOR Brains Minds+ Machines

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Undergraduate Curriculum for the Science and Engineering of Intelligence

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Abstract

Many undergraduate majors, combined with a complement of coursework in computer science, mathematics, neuroscience, and cognitive science, can prepare students for graduate work focused on the interdisciplinary study of intelligence. This document highlights some core areas within key disciplines, for which training at an introductory or intermediate level is valuable for research on intelligence that integrates computational and empirical approaches, and notes some of the contexts in which this training is applied. We also outline several existing academic programs at partner institutions of the Center for Brains, Minds, and Machines, that integrate cross-disciplinary training in different ways. This is an evolving document that is intended to assist students and faculty in the formulation of a program of undergraduate study that provides effective training for advanced work in the science and engineering of intelligence.

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Introduction

Many undergraduate majors, combined with a complement of coursework in computer science, mathematics, neuroscience, and cognitive science, can prepare students for graduate work focused on the interdisciplinary study of intelligence. This document highlights some core areas within key disciplines, for which training at an introductory or intermediate level is valuable for research on intelligence that integrates computational and empirical approaches. We also note some of the contexts in which this training is applied. This is an evolving document that is intended to assist students and faculty in the formulation of a program of undergraduate study that provides effective training for advanced work in the science and engineering of intelligence.

One of the challenges for the design of a suitable program of study concerns how to obtain broad exposure to relevant disciplines at an introductory or intermediate level, without sacrificing the depth of training within a particular area that is critical for graduate research. The success of the CBMM research program, and work in this field more broadly, depends on collaborations between researchers that bring a depth of expertise from different disciplines, research approaches, and methodologies. Among the academic partners of the Center, there are examples of rigorous interdisciplinary undergraduate programs that balance breadth and depth in different ways. Later in this document, we briefly outline several existing programs, some of which could be tailored more closely to the study of intelligence. We also note some factors that hinder the pursuit of broad interdisciplinary training at the undergraduate level, and ways to complement coursework with other academic opportunities.

Broad Aims and Scope of Undergraduate Training in Intelligence Science

In the CBMM Strategic Plan, the ultimate goal of academic training at the undergraduate and graduate levels is captured in the following integrated outcome for education:

> *Students well-prepared to become future research and education leaders in the new field of the Science and Engineering of Intelligence, with integrated knowledge and skills in computation, neuroscience, and cognitive science.*

Ideally, undergraduate training should lay the foundation for advanced graduate study or for direct entry into industry or other professions that draw on intelligence science. As with any science, this training should enable students to learn the fundamental concepts and methods of the field, demonstrate how the empirical and theoretical tools of component disciplines can be used to analyze and develop solutions to problems, and articulate and evaluate evidence in support of scientific or formal theories of intelligence. Undergraduate training should extend beyond course specific technical knowledge and classroom activities, to include research or project based independent or collaborative learning experiences and additional opportunities to develop oral and written technical communication skills. It should also include exposure to important ethical issues, the responsible conduct of research, and the impact of intelligence research on society. Opportunities for such broad research training are often embodied in undergraduate honors programs.

Primary Areas of Academic Study for Intelligence Science

This section highlights some core areas within key disciplines, for which training at an introductory or intermediate level is especially valuable for the study of intelligence, and notes some of the contexts in which this training is applied. Core areas are specified at a level that is typically associated with single undergraduate courses. In some areas, the curriculum is fairly standardized (e.g. math and physics courses). In areas where there is greater variability across institutions, many instantiations of the subject matter can provide adequate training (e.g. introductory computer science or AI courses). An undergraduate program focused on intelligence science may include core academic training that is fundamental to most work in this field, combined with an area of specialization that provides deeper training in particular methodologies or domains. For each discipline below, we also note some useful areas of intermediate or advanced study. Within any of these subject areas, advanced courses on research methods, seminar or directed reading courses focused on research, and project based independent study courses, help students to develop important background and skills for graduate research. Opportunities to take courses whose curriculum spans different disciplines can provide useful training on the integration of multiple perspectives and research methods, emphasizing the development of *interdisciplinary thinking*.

Mathematics:
Training in mathematics is essential for the development and analysis of models of intelligence, and for many aspects of the empirical study of intelligence, including experimental design and implementation, and the analysis, visualization, and interpretation of data.

> **Core areas:** calculus (single and multivariable); linear algebra; probability and statistics

Students interested in studying more deeply, the computational or theoretical aspects of models of intelligence, or advanced quantitative methods of experimental design and data analysis, should have more extensive training in mathematics. Work in computational neuroscience and cognition also draws on background in areas such as differential equations and logic.

Physics:
In addition to being a foundational domain of application of important mathematics skills, training in physics is especially relevant for aspects of intelligence involving interaction with and interpretation of the physical world. Physics is also essential for modeling the behavior of neurons and neural circuits, and for the design of advanced technologies for probing the behavior of neural circuits in the brain.

> **Core areas:** classical mechanics; electricity and magnetism

A calculus based introduction to these areas provides stronger preparation for work in this field, relative to an algebra based presentation. Advanced work on the theoretical aspects of modeling intelligence, including domains such as vision, audition, and motor control, and study of the detailed mechanisms by which computations are implemented in neural hardware, draw on deeper training in physics.

Computer Science:
Background in computer science is essential for the development, implementation, and analysis of models of intelligence, as well as many aspects of the empirical study of intelligence including the design and implementation of experiments, and analysis and visualization of data.

> **Core areas:** introduction to programming and computational thinking; artificial intelligence; machine learning

The engineering of advanced intelligent systems draws on further training in computer science that includes advanced courses in AI and machine learning, theoretical background in algorithms and computational complexity, or training in software engineering and computer graphics. Advanced AI courses might focus on domains such as visual processing, natural language understanding, robotics, planning, knowledge representation, and commonsense reasoning. Advanced machine learning courses may focus on approaches such as probabilistic modelling or statistical learning theory, deep learning networks, or reinforcement learning.

Engineering:
Advances in empirical methods used in neuroscience research to probe neural circuits rely on broad engineering training. Models of neuronal behavior draw from background in circuits and electronics, and many areas of computational neuroscience use techniques from signal processing and systems. Applications of signal processing also arise within domains of intelligence such as vision, audition, and motor control, in both biological systems and computer or robotic systems.

> **Core areas:** circuits and electronics; signals and systems

Advanced project based work that applies the principles of engineering design is also valuable for the construction of intelligent systems.

Neuroscience:
Background in neuroscience is essential for studying intelligence in humans and other biological systems. Subareas within the field emphasize different aspects of the structure and function of the brain and peripheral systems that are engaged in intelligent behavior. These subareas include cellular and molecular neuroscience, systems neuroscience, computational neuroscience, cognitive neuroscience, and developmental neurobiology. Each subarea draws on background from other disciplines, as its name suggests. Exposure to modern methods for probing the brain, and the knowledge of brain function and behavior that has emerged from these methods, are valuable for intelligence research.

> **Core area:** introduction to neuroscience

Relevant topics that may be covered in an introductory neuroscience course include the structure and function of neurons, functional organization of the brain, sensory and motor systems, learning and memory, common empirical methods such as single cell recording and brain imaging techniques including fMRI, and the neural basis and behavioral consequences of brain disease. Advanced courses might focus on the neuroscientific study of particular domains, such as vision and other sensory systems, motor control, learning and memory, or speech and language processing. An advanced course might also focus on the broad application of methodologies such as fMRI and other neuroimaging techniques.

Cognitive Science and Psychology:
Background in cognitive science and psychology is important for the study of many aspects of human intelligence and its development from infancy through adulthood. Background in the research methods used in empirical and modeling studies, and the understanding of cognitive and perceptual behavior and representation of knowledge that has emerged from the application of these methods, is essential for advanced work in intelligence science.

Core area: introduction to cognitive science

An introductory course might cover the mental processes underlying, for example, perception, emotion, learning, memory, language, cognition, decision making, consciousness, cognitive development, or social interaction. Intermediate and advanced courses might explore any of these topics in greater depth, including the integration of behavioral, computational, neural, and developmental perspectives on how these processes are carried out in the brain.

Interdisciplinary Undergraduate Programs in Brain Science

Interdisciplinary undergraduate programs in brain science that integrate training in computation, neuroscience, and cognitive science, have emerged over the past few decades. Many programs combine core training with concentrations that provide in-depth training in particular subfields, and include courses from multiple departments among the required or elective courses that can be counted toward the major. The following are some examples, including CBMM academic partners and a few non-partner institutions. Although not specifically focused on intelligence, course choices can often be tailored to emphasize topics relevant to the study of intelligence.

Brain and Cognitive Sciences Program at MIT
The MIT Brain and Cognitive Sciences department is highly interdisciplinary, with many CBMM faculty. The undergraduate major is described on these pages: http://catalog.mit.edu/degree-charts/brain-cognitive-sciences-course-9/ and https://bcs.mit.edu/academic-program/undergraduate. Core requirements include introductory courses in psychological science, neuroscience, neural computation, computer science, probability and statistics. Students create a program of intermediate and advanced courses in an area of concentration such as systems neuroscience, cognitive science, or computation. Up to four restricted electives from other departments can be counted toward the major, including many math, computer science, and electrical engineering courses.

Mind/Brain/Behavior Program at Harvard

The Mind/Brain/Behavior Interfaculty Initiative at Harvard was established to foster research and educational activities that bridge the community of faculty and students interested in the mind, brain, and behavior. Academic tracks for undergraduates integrate introductory courses in psychological science and neuroscience, an advanced seminar, and major concentration drawn from computer science, history and science, human evolutionary biology, linguistics, philosophy, neuroscience/neurobiology, or psychology (http://mbb.harvard.edu/pages/undergraduate). Each concentration has guidelines on how the associated departmental major requirements can be satisfied with courses that emphasize the brain, mind, and behavior. Students are required to complete senior thesis research and participate in an interdisciplinary symposium (junior year) and research workshop (senior year) that emphasize interactions among students across tracks. Upon completion of these requirements, students are awarded a Certificate in Mind/Brain/Behavior in addition to their A.B. degree.

Neuroscience Program at Wellesley College

The Wellesley Neuroscience Program (http://www.wellesley.edu/neuroscience/major) offers a rigorous major that integrates core training in neuroscience at the introductory, intermediate and advanced levels with coursework that can be drawn from biology, psychology, chemistry, computer science, math, and physics. Students pursue one of three areas of concentration that include cellular and molecular neuroscience, cognitive neuroscience, and systems and computational neuroscience. A capstone seminar for majors emphasizes current literature on cutting edge research areas in neuroscience.

Quantitative Biology Program and Neuroscience Concentration at Hunter College

The Quantitative Biology program at CUNY Hunter College (http://www.hunter.cuny.edu/qubi) is similar in some ways to the Harvard Mind/Brain/Behavior program. Students take core courses in biology, chemistry, math and statistics, and complete a quantitative biology concentration in one of several majors: biology, chemistry, computer science, mathematics, or statistics. As stated on the program website, *"Among the many benefits of this innovative program are access to competitive scholarships, small classes, training by a multidisciplinary team of research scientists and dedicated academics, individual mentoring, the opportunity to participate in research conducted at Hunter and nationally, topnotch preparation for graduate studies and for scientific careers in this new frontier."* Hunter College also offers a research oriented concentration in behavioral neuroscience in the psychology major that integrates coursework in psychology and biology and includes an Honors option (http://www.hunter.cuny.edu/psychology/undergraduate-studies/psychology-concentration-in-behavioral-neuroscience).

Other Related Programs

The University of Rochester offers both BA and BS degrees in Brain and Cognitive Sciences (http://www.bcs.rochester.edu/undergrad/). Similar to the Brain and Cognitive Sciences major at MIT, the BS degree incorporates individualized concentrations that include coursework from several allied fields (http://www.sas.rochester.edu/bcs/undergraduate/BSdegree.html). CMU offers a minor in Neural Computation jointly sponsored by the School of Computer Science, the Mellon College of Science, and the College of Humanities and Social Sciences, and coordinated by the Center for Neural Basis of Cognition (http://www.cnbc.cmu.edu/upnc/nc_minor/). The primary objective of this new minor is *"to encourage students in biology and psychology to take computer science, engineering and mathematics courses on the one hand, and to encourage students in computer science, engineering, statistics and physics to take courses in neuroscience and psychology on the other, and to bring students from different disciplines together to form a community."* Tufts University offers a concentration in cognitive and brain sciences that draws on psychology, linguistics, neuroscience, philosophy, computer science, and biology, in which students are also encouraged to complete a senior research project (http://ase.tufts.edu/psychology/undergraduate/concCognitive.htm). Finally, RPI offers a fairly structured interdisciplinary BS degree in cognitive science that integrates many of the core areas enumerated earlier in this document (http://www.cogsci.rpi.edu/pl/bs-cognitive-science).

Challenges for Broad Undergraduate Training in Intelligence Science

As noted earlier, one of the challenges in designing an undergraduate curriculum arises from the need to balance breadth of training in several disciplines with the deep training in a particular area that is essential for advanced work in the field. The previous section listed some examples of undergraduate programs that balance these needs in different ways. These existing programs do not focus on intelligence per se, but can be tailored to emphasize training related to this field or serve as models for the design of new programs focused on the science and engineering of intelligence. All of the CBMM academic partner schools with undergraduate programs, for example, offer courses in all, or nearly all of the core areas listed earlier, but additional challenges may hinder students' ability to pursue this broad academic training. It may be difficult, for example, to integrate within a single major, courses taught in departments that are housed in different schools within the institution (e.g. across a School of Arts and Sciences and School of Engineering). A key subject area, such as machine learning, may only be offered at an advanced level that follows an extended sequence of prerequisite courses that may not all be relevant to a student's interests. The subject matter itself may be divided into a two-course sequence that adds to a student's course load. As noted earlier, many undergraduate majors in science and engineering can prepare students for advanced work in this field. Most schools have broad distribution or general education requirements, some of which may be satisfied with courses outside a student's major that are relevant to the study of intelligence.

Summary

This document briefly outlined areas of study that provide useful academic preparation at the undergraduate level, for students interested in graduate work in the interdisciplinary science and engineering of intelligence. It also noted examples of existing academic programs that integrate this training in a single major or certificate program. We also encourage students to complement their coursework with undergraduate research or other experiential learning activities; to attend research seminars and scientific meetings in the field, and to explore online resources for independent learning, such as resources available at the CBMM website (http://cbmm.mit.edu/) and Science of Intelligence Learning Hub (http://cbmm.mit.edu/learning-hub).