Applied Mathematics

The Division of Applied Mathematics at Brown University is one of the most prominent departments at Brown, and is also one of the oldest and strongest of its type in the country. The Division of Applied Mathematics is a world renowned center of research activity in a wide spectrum of traditional and modern mathematics. It explores the connections between mathematics and its applications at both the research and educational levels. The principal areas of research activities are ordinary, functional, and partial differential equations: stochastic control theory; applied probability, statistics and stochastic systems theory; neuroscience and computational molecular biology; numerical analysis and scientific computation; and the mechanics of solids, materials science and fluids. The effort in virtually all research ranges from applied and algorithmic problems to the study of fundamental mathematical questions. The Division emphasizes applied mathematics as a unifying theme. To facilitate cooperation among faculty and students, some research programs are partly organized around interdepartmental research centers. These centers facilitate funding and cooperative research in order to maintain the highest level of research and education in the Division. It is this breadth and the discovery from mutual collaboration which marks the great strength and uniqueness of the Division of Applied Mathematics at Brown.

For additional information, please visit the department's website: https://www.brown.edu/academics/applied-mathematics/

Applied Mathematics Concentration Requirements

Applied Mathematics has a profound impact on our daily lives. Whether it is search engines, climate modeling, weather forecasts, artificial intelligence, secure online shopping, brain imaging, or movie recommendations, none of these would work the way they do without algorithms and tools from the mathematical sciences. More generally, Applied Mathematics is an inherently interdisciplinary subject, covering problems arising in all areas of science, technology, and engineering. Our courses provide a broad qualitative and quantitative background for use in these fields.

Applied Mathematics appeals to people with a variety of different interests, ranging from those with a desire to obtain a good quantitative background for use in some future career, to those who wish to have a better understanding of the basic mathematical aspects of other fields, or to those who are interested in the fundamental mathematical techniques and approaches in themselves. The program stresses but is not limited to scientific computing, differential equations, probability, and statistics, which are areas of mathematics that are used most often in applications in science, society, and industry. Our curriculum is flexible enough to meet the goals and interests of a very wide range of students.

Students take courses in applied mathematics for many reasons, not necessarily with an applied mathematics concentration in mind. The value of learning about applied mathematics goes beyond a career opportunity. It provides an education in the use of quantitative methods in thinking about and solving problems, knowledge that is valuable in all walks of life.

We offer four concentrations for undergraduates: Applied Mathematics (A.B. & Sc.B.), Applied Mathematics-Biology (Sc.B.), Applied Mathematics-Computer Science (Sc.B.), Applied Mathematics-Economics (A.B. & Sc.B.). This page describes the concentration in Applied Mathematics.

The concentration in Applied Mathematics is the most flexible of all of our concentrations. Students are required to build a foundation in calculus, linear algebra, differential equations, and basic computer programming. Beyond these foundations, there is a great deal of flexibility as to which areas of mathematics and which areas of applications are pursued. Both the A.B. and the Sc.B. allow students to earn concentration credit by taking advanced courses in almost any of the STEM (Science, Technology, Engineering, Mathematics) disciplines. The purpose is to encourage students to develop expertise in both mathematics and an applied area that might be amenable to mathematical investigation.

Standard program for the A.B. degree.

Prerequisites - the equivalent of two semesters of single-variable calculus		
Single-variable calculus is not an enforced requirement for our concentration, but it is a required prerequisite for many of our courses. At Brown, single-variable calculus consists of MATH 0090 followed by one of MATH 0100, MATH 0170, or MATH 0190.		
Requirements - 10 courses [1]		
MATH 0180	Multivariable Calculus	1
or MATH 0200	Multivariable Calculus (Physics/Engineering)	
or MATH 0350	Multivariable Calculus With Theory	
MATH 0520	Linear Algebra	1
or MATH 0540	Linear Algebra With Theory	
APMA 0350	Applied Ordinary Differential Equations [2]	1
APMA 0360	Applied Partial Differential Equations I [3]	1
One approved course on computer programming. [4]		1
Three 1000-level or higher APMA courses. [5]		3
One 1000-level or higher APMA or MATH course. [5]		1
One 1000-level or higher course in a STEM discipline that demonstrates depth in an area amenable to mathematical investigation and that is approved by the concentration advisor. [6]		1
Total Credits		**10**

1. A required course may be replaced by a more advanced course with concentration advisor approval. No course may be used to satisfy multiple concentration requirements. Transfer credits and courses receiving placement credit notation can satisfy concentration credit as long as they appear on the Brown internal transcript. Pursuing honors will require 12 courses – these 10 plus two additional semesters of independent study courses for the honors research project. For students with multiple concentrations, calculus, linear algebra, and at most two additional courses can be used for concentration credit in the other concentration(s).
2. APMA 0330 or MATH 1110 may be used in place of APMA 0350. If MATH 1110 is used, then the concentration must include at least four 1000-level or higher APMA courses (not including APMA 1910, APMA 1920, or research/independent study courses). These can appear anywhere in the declaration.
3. APMA 0340 or MATH 1120 may be used in place of APMA 0360. If MATH 1120 is used, then the concentration must include at least four 1000-level or higher APMA courses (not including APMA 1910, APMA 1920, or research/independent study courses). These can appear anywhere in the declaration.
4. Concentrators are encouraged to complete the computing requirement before the end of their sophomore year. The following courses are automatically approved: APMA 0160, APMA 0200, CSCI 0111, CSCI 0150, CSCI 0170, CSCI 0190, CSCI 0200, CLPS 0950, EEPS 0250.
5. APMA 1910, APMA 1920, and research/independent study courses cannot be used.
6. STEM = Science, Technology, Engineering, Mathematics. Most upper-level courses in APMA, CSCI, ECON, ENGN, MATH, or any of the sciences will be approved, including APMA 1910, APMA 1920. Upper-level courses in other areas may also be approved if the connection to applied mathematics is clear. Concentration advisors may approve a group of lower-level courses as a substitute for a single upper-level course if the group collectively demonstrates depth in a STEM area. Lower-level APMA, CSCI, and MATH courses and independent study/research courses cannot be used.

Standard program for the Sc.B. degree.

Prerequisites - the equivalent of two semesters of single-variable calculus

Single-variable calculus is not an enforced requirement for our concentration, but it is a required prerequisite for many of our courses. At Brown, single-variable calculus consists of MATH 0090 followed by one of MATH 0100, MATH 0170, or MATH 0190.

Requirements - 16 courses [1]

MATH 0180	Multivariable Calculus	1
or MATH 0200	Multivariable Calculus (Physics/Engineering)	
or MATH 0350	Multivariable Calculus With Theory	
MATH 0520	Linear Algebra	1
or MATH 0540	Linear Algebra With Theory	
APMA 0350	Applied Ordinary Differential Equations [2]	1
APMA 0360	Applied Partial Differential Equations I [3]	1
One approved course on computer programming. [4]		1
Four 1000-level or higher APMA courses. [5]		4
Two 1000-level or higher APMA or MATH courses. [5]		2
Four 1000-level or higher courses in one or more STEM disciplines that demonstrate depth in areas amenable to mathematical investigation and that are approved by the concentration advisor. [6]		4
One approved capstone, senior seminar, or research-related course. [7]		1
Total Credits		**16**

1. A required course may be replaced by a more advanced course with concentration advisor approval. No course may be used to satisfy multiple concentration requirements. Transfer credits and courses receiving placement credit notation can satisfy concentration credit as long as they appear on the Brown internal transcript. Pursuing honors will require 17 courses – these 16 along with two semesters of independent study courses for the honors research project, one of which can be used to satisfy the capstone concentration requirement. For students with multiple concentrations: calculus, linear algebra, one intro CSCI course, and at most two additional courses can be used for concentration credit in the other concentration(s).
2. APMA 0330 or MATH 1110 may be used in place of APMA 0350. If MATH 1110 is used, then the concentration must include at least five 1000-level or higher APMA courses (not including APMA 1910, APMA 1920, or research/independent study courses). These can appear anywhere in the declaration.
3. APMA 0340 or MATH 1120 may be used in place of APMA 0360. If MATH 1120 is used, then the concentration must include at least five 1000-level or higher APMA courses (not including APMA 1910, APMA 1920, or research/independent study courses). These can appear anywhere in the declaration.
4. Concentrators are encouraged to complete the computing requirement before the end of their sophomore year. The following courses are automatically approved: APMA 0160, APMA 0200, CSCI 0111, CSCI 0150, CSCI 0170, CSCI 0190, CSCI 0200, CLPS 0950, EEPS 0250.
5. APMA 1910, APMA 1920, and research/independent study courses cannot be used.
6. STEM = Science, Technology, Engineering, Mathematics. Most upper-level courses in APMA, CSCI, ECON, ENGN, MATH, or any of the sciences will be approved, including APMA 1910, APMA 1920. Upper-level courses in other areas may also be approved if the connection to applied mathematics is clear. Concentration advisors may approve a group of lower-level courses as a substitute for a single upper-level course if the group collectively demonstrates depth in a STEM area. Lower-level APMA, CSCI, and MATH courses and independent study/research courses cannot be used.
7. The following courses are automatically approved: APMA 1360, APMA 193*/194* (where * is any combination of numbers and letters; these are the APMA senior seminars), an independent study course used to satisfy the APMA honors requirement.

Professional Tracks

The requirements for the professional tracks include all those of each of the standard tracks, as well as the following:

Students must complete full-time professional experiences doing work that is related to their concentration programs, totaling 2-6 months, whereby each internship must be at least one month in duration in cases where students choose to do more than one internship experience. Such work is normally done at a company, but may also be at a university under the supervision of a faculty member. Internships that take place between the end of the fall and the start of the spring semesters cannot be used to fulfill this requirement.

On completion of each professional experience, the student must write and upload to ASK a reflective essay about the experience, to be approved by the student's concentration advisor, addressing these questions:

- Which courses were put to use in your summer's work? Which topics, in particular, were important?
- In retrospect, which courses should you have taken before embarking on your summer experience? What are the topics from these courses that would have helped you over the summer if you had been more familiar with them?
- Are there topics you should have been familiar with in preparation for your summer experience, but are not taught at Brown? What are these topics?
- What did you learn from the experience that probably could not have been picked up from course work?
- Is the sort of work you did over the summer something you would like to continue doing once you graduate? Explain.
- Would you recommend your summer experience to other Brown students? Explain.

Honors

Concentrators (A.B. or Sc.B.) that demonstrate excellence in grades and in undergraduate research can be awarded departmental honors. Complete guidelines, requirements, and deadlines for honors are published on the department website (https://appliedmath.brown.edu/academics/undergraduate-program/honors/). The first deadline is at the beginning of the student’s senior year (i.e., the start of the penultimate semester). The main requirements include:

- Earning grades of A or S-with-distinction in at least 70% of the courses used for concentration credit, excluding calculus and linear algebra, by the end of the penultimate semester.
- Completion of an in-depth, original research project in a STEM discipline carried out under the guidance of a Brown-affiliated faculty advisor and documented with the completion of two semesters of independent study courses under the advisor’s supervision.
- Completion of an honors thesis describing this research project that also demonstrates the use of mathematical methodology in the project. The honors thesis must be approved by the student’s thesis advisor and a second reader, at least one of which must be faculty member in the Division of Applied Mathematics.

Applied Mathematics-Biology Concentration Requirements

Biology, the science of all life and living matter, is an incredibly diverse discipline offering students the opportunity to learn about topics ranging from the fundamental chemical reactions that fuel all living organisms to the population dynamics of entire ecosystems all the way to the question of how our brains give rise to the complexities of human cognition and experience. Applied mathematics is an increasingly important component of modern biological investigation. Modern technologies have enabled the creation of vast new biological data sets that often require sophisticated mathematical and statistical models for interpretation and analysis. Advances in computing have similarly enabled the simulation of biological phenomena at increasingly fine levels of detail. Entire subfields, such as bioinformatics and computational neuroscience, have developed around these new paradigms of biological investigation. The foundations of these new fields are inherently mathematical, with a focus on probability, statistical inference, and systems dynamics.

The Applied Mathematics – Biology concentration allows students to develop complementary expertise in biology and applied mathematics. Students will focus their advanced biological coursework in an area of particular interest to them. The applied math requirements emphasize those areas of mathematics that have found widespread use throughout all of the biological sciences. The program culminates in a senior capstone experience that enables students to participate in creative research collaborations with faculty.

Standard program for the Sc.B. degree

Prerequisites – the equivalent of two semesters of single-variable calculus		
Single-variable calculus is not an enforced requirement for our concentration, but it is a required prerequisite for many of our courses. At Brown, single-variable calculus consists of MATH 0090 followed by one of MATH 0100, MATH 0170, or MATH 0190.		
Requirements – 16 courses [1]		
Mathematical Requirements – 7 courses		
MATH 0180	Multivariable Calculus	1
or MATH 0200	Multivariable Calculus (Physics/Engineering)	
or MATH 0350	Multivariable Calculus With Theory	
MATH 0520	Linear Algebra	1
or MATH 0540	Linear Algebra With Theory	
APMA 0350	Applied Ordinary Differential Equations [2]	1
APMA 0360	Applied Partial Differential Equations I [3]	1
APMA 1655	Honors Statistical Inference I	1
or APMA 1650	Statistical Inference I	
APMA 1070	Quantitative Models of Biological Systems	1
APMA 1080	Inference in Genomics and Molecular Biology	1
or NEUR 2110	Statistical Neuroscience	
Scientific Requirements – 7 courses		
One approved course (or course grouping) covering Newtonian mechanics. [4]		1
CHEM 0330	Equilibrium, Rate, and Structure	1
BIOL 0200	The Foundation of Living Systems [5]	1
Two approved courses in the biological sciences. All four biological electives (two here and two in the next requirement) should form a cohesive grouping in a specific area of biological interest. [6]		2
Two approved 1000-level or higher courses in the biological sciences. All four biological electives (two here and two in the previous requirement) should form a cohesive grouping in a specific area of biological interest. [6]		2
Additional Requirements – 2 courses		
One approved course in the mathematical, biological, or computational sciences. [7]		1
One approved capstone, senior seminar, or research-related course in the mathematical or biological sciences. [8]		1
Total Credits		**16**

1 A required course may be replaced by a more advanced course with concentration advisor approval. No course may be used to satisfy multiple concentration requirements. Transfer credits and courses receiving placement credit notation can satisfy concentration credit as long as they appear on the Brown internal transcript. Pursuing honors will require 17 courses – these 16 along with two semesters of independent study courses for the honors research project, one of which can be used to satisfy the capstone concentration requirement. For students with multiple concentrations: calculus, linear algebra, one intro CSCI course, and at most two additional courses can be used for concentration credit in the other concentration(s).

2 APMA 0330 or MATH 1110 may be used in place of APMA 0350. If MATH 1110 is used, then the concentration must include at least three 1000-level APMA courses (not including APMA 1910, APMA 1920 or research/independent study courses).

3 APMA 0340 or MATH 1120 may be used in place of APMA 0360. If MATH 1120 is used, then the concentration must include at least three 1000-level APMA courses (not including APMA 1910, APMA 1920 or research/independent study courses).

4 PHYS 0050 or PHYS 0070 are recommended. The following course(s) are automatically approved: PHYS 0030, PHYS 0050, PHYS 0070, ENGN 0031, ENGN 0030 + ENGN 0040, (one of ENGN 0030, ENGN 0040) + (one of PHYS 0040, PHYS 0060, a score of 3 or higher on any AP Physics, a score of 4 or higher on IB-HL Physics). When considering alternative course(s) a key criterion is whether both statics and dynamics are covered.

5 A BIOL placement test score of 30 or higher may be used in place of BIOL 0200. The placement test score can be found in ASK, in the advising detail view, under the test scores section. This will reduce by 1 credit the number of credits needed to complete the concentration.

6 A wide variety of areas are possible, such as, biochemistry, physiology, biotechnology, ecology, genetics, virology, evolution, neuroscience, immunopathology, molecular biology, etc. Courses in BIOL, NEUR, CHEM are quite common. An important consideration is that foundational biological knowledge is emphasized. If, for instance, most of the courses were in biostatistics and the emphasis was more statistical than biological, then this would not be an approved collection.

7 1000-level courses in APMA, BIOL, CSCI, MATH, NEUR are automatically approved, including APMA 1910, APMA 1920. Research/independent study courses cannot be used. Concentrators are strongly encouraged to use this requirement to develop their computer programming skills and to do so before the end of sophomore semester. Many upper-level APMA courses, including APMA 1080, require exposure to programming as a prerequisite. The following courses are automatically approved for this purpose: APMA 0160, APMA 0200, CSCI 0111, CSCI 0150, CSCI 0170, CSCI 0190, CSCI 0200, CLPS 0950, EEPS 0250.

8 The following options can be used to satisfy this requirement

- A pre-approved course that satisfies the APMA Sc.B. capstone requirement: currently APMA 1360, APMA 193*/194* (where * is any combination of numbers and letters; these are the APMA senior seminars).
- A pre-approved course that satisfies the Biology A.B. capstone requirement: currently BIOL 1100, BIOL 1250,BIOL 1515, BIOL 1555, BIOL 1565, BIOL 1575, BIOL 1600, BIOL 1820, BIOL 1970A.
- A directed research/independent study course from the APMA 1970/ APMA 1971, BIOL 1950/BIOL 1960, or NEUR 1970 series that is used for undergraduate research. For students pursuing honors in APMA-Bio, one of the two required semesters of independent study courses can be used.
- A directed research/independent study course in a related discipline (i.e. STEM disciplines, ENVS, PHP, etc.) if the project is relevant to the student's learning goals in the concentration and with approval from the concentration advisor.
- A non-research course related to the concentration in addition to a research experience equivalent in scope and scale to work the student would pursue in an Applied Math or Biology research-related independent study course. Examples include UTRAs, LINK awards, research programs at other institutions, etc. This requires approval from the concentration advisor and appropriate documentation that should be uploaded to ASK.
- Other equivalent opportunities not listed, with approval from the concentration advisor. Documentation should be uploaded to ASK.

Professional Tracks

The requirements for the professional tracks include all those of each of the standard tracks, as well as the following:

Students must complete full-time professional experiences doing work that is related to their concentration programs, totaling 2-6 months, whereby each internship must be at least one month in duration in cases where students choose to do more than one internship experience. Such work is normally done at a company, but may also be at a university under the supervision of a faculty member. Internships that take place between the end of the fall and the start of the spring semesters cannot be used to fulfill this requirement.

On completion of each professional experience, the student must write and upload to ASK a reflective essay about the experience, to be approved by the student's concentration advisor, addressing these questions:

- Which courses were put to use in your summer's work? Which topics, in particular, were important?
- In retrospect, which courses should you have taken before embarking on your summer experience? What are the topics from these courses that would have helped you over the summer if you had been more familiar with them?
- Are there topics you should have been familiar with in preparation for your summer experience, but are not taught at Brown? What are these topics?
- What did you learn from the experience that probably could not have been picked up from course work?
- Is the sort of work you did over the summer something you would like to continue doing once you graduate? Explain.
- Would you recommend your summer experience to other Brown students? Explain.

Honors

Concentrators that demonstrate excellence in grades and in undergraduate research can be awarded departmental honors. Honors students with primary advisors in Applied Math should follow the guidelines, requirements, and deadlines for honors as described in the bulletin for Applied Math concentrators (https://bulletin.brown.edu/the-college/concentrations/apma/) and as published on the APMA departmental website (https://appliedmath.brown.edu/academics/undergraduate-program/honors/). Honors students with primary advisors in Biomed should follow the guidelines, requirements, and deadlines for honors as described in the bulletin for Biology concentrators (https://bulletin.brown.edu/the-college/concentrations/biol/) and as published on the Biology departmental website (https://bue.brown.edu/academics/honors/). Students wishing to do honors research with a non-APMA or Biomed advisor should contact the Directors of Undergraduate Studies in APMA and Biology to discuss options.

Applied Mathematics-Computer Science Concentration Requirements

The Sc.B. concentration in Applied Math-Computer Science provides a foundation of basic concepts and methodology of mathematical analysis and computation and prepares students for advanced work in applied mathematics, computer science, and data science. Concentrators must complete courses in mathematics, applied math, computer science, and an approved English writing course. While the concentration in Applied Math-Computer Science allows students to develop the use of quantitative methods in thinking about and solving problems, knowledge that is valuable in all walks of life, students who have completed the concentration have pursued graduate study, computer consulting and information industries, and scientific and statistical analysis careers in industry or government. This degree offers a standard track and a professional track.

Standard Program for the Sc.B. degree.

Prerequisites – the equivalent of two semesters of single-variable calculus

A second semester of single-variable calculus is not an enforced requirement for our concentration, but it is a required prerequisite for many of our courses. At Brown, the second semester of calculus is taught in one of MATH 0100, MATH 0170, or MATH 0190.		
Requirements – 17 courses [1,2]		
Completion of one APMA pairing [3]		
Mathematical Requirements – 8 courses		
MATH 0180	Multivariable Calculus [4]	1
or MATH 0200	Multivariable Calculus (Physics/Engineering)	
or MATH 0350	Multivariable Calculus With Theory	
MATH 0520	Linear Algebra [4]	1
or MATH 0540	Linear Algebra With Theory	
or CSCI 0530	Coding the Matrix: An Introduction to Linear Algebra for Computer Science	
or APMA 1170	Introduction to Computational Linear Algebra	
APMA 0350	Applied Ordinary Differential Equations [5]	1
APMA 0360	Applied Partial Differential Equations I [6]	1
APMA 1160	An Introduction to Numerical Optimization	1
or APMA 1170	Introduction to Computational Linear Algebra	
or APMA 1180	Introduction to Numerical Solution of Differential Equations	
or APMA 1690	Computational Probability and Statistics	
or APMA 1740	Recent Applications of Probability and Statistics	
Two approved 1000-level or higher APMA courses. The APMA pairing must be completed. [3,7,8]		2
One 1000-level or higher APMA or MATH course [7,8]		1
Computer Science Requirements – 8 courses [2]		
Select one of the following introductory course sequences		2
CSCI 0150 & CSCI 0200	Introduction to Object-Oriented Programming and Computer Science and Program Design with Data Structures and Algorithms	
CSCI 0170 & CSCI 0200	Computer Science: An Integrated Introduction and Program Design with Data Structures and Algorithms	
CSCI 0111 & CSCI 0200	Computing Foundations: Data and Program Design with Data Structures and Algorithms [2]	
CSCI 0190 and one CSCI course numbered 0200 or higher		
Select one foundational course in each of three of the following four clusters:		3
a. Algorithms/Theory Foundations		
CSCI 0500	Data Structures, Algorithms, and Intractability: An Introduction	
CSCI 1010	Theory of Computation	
CSCI 1550	Probabilistic Methods in Computer Science	
CSCI 1570	Design and Analysis of Algorithms	
b. AI/Machine Learning/Data Science Foundations		
CSCI 0410	Foundations of AI	
CSCI 1410	Artificial Intelligence	
CSCI 1411	Foundations in AI	
CSCI 1420	Machine Learning	
CSCI 1430	Computer Vision	
CSCI 1460	Computational Linguistics	
CSCI 1470	Deep Learning	
CSCI 1850	Deep Learning in Genomics	
CSCI 1951A	Data Science	
c. Systems Foundations [9]		
CSCI 0300	Fundamentals of Computer Systems	

CSCI 0320	Introduction to Software Engineering	
CSCI 0330	Introduction to Computer Systems	
d. Probability [8, 10]		
APMA 1655	Honors Statistical Inference I	
APMA 1650	Statistical Inference I	
CSCI 1450	Advanced Introduction to Probability for Computing and Data Science	
MATH 1210	Probability	
MATH 1610	Probability	
Three approved 1000-level or higher CSCI courses, which cannot include arts/policy/humanities courses [11]		3
Additional Requirements – 1 course		**1**
One approved capstone in computer science or applied mathematics taken in the student's senior year. [12]		
Total Credits		**17**

1 A required course may be replaced by a more advanced course with concentration advisor approval. No course may be used to satisfy more than one of the required 17 concentration credits. Transfer credits and courses receiving placement credit notation can satisfy concentration credit as long as they appear on the Brown internal transcript. At most 3 post-matriculation transfer credits (such as study abroad courses or summer courses at another institution) can be used for concentration credit. Pursuing honors will require 18 courses – these 17 along with two semesters of independent study courses for the honors research project, one of which can be used to satisfy the capstone concentration requirement. For students with multiple concentrations: calculus, linear algebra, one intro CSCI course, and at most two additional courses can be used for concentration credit in the other concentration(s).

2 Students who take the CSCI 0111, CSCI 0112, CSCI 0200 sequence will effectively need an additional course (CSCI 0112) to complete the concentration. Students wishing to go directly from CSCI 0111 to CSCI 0200 (without CSCI 0112) will need to successfully complete additional exercises to receive an instructor override code for CSCI 0200.

3 To complete an APMA pairing, students must complete two 1000-level or higher APMA courses that adhere to a common theme. These courses can appear anywhere in the declaration. APMA 1910, 1920, and research/independent study courses are not allowed. Themes can be broadly defined and are subject to concentration advisor approval. Examples include:

- Probability and statistics: APMA 1080, APMA 1200, APMA 1650/APMA 1655, APMA 1660, APMA 1690, APMA 1710, APMA 1720, APMA 1740/ APMA 2610, APMA 1860, APMA 1930V, APMA 1930W, APMA 1930X, APMA 1941D, APMA 1941E, APMA 2630, APMA 2640, APMA 2670,APMA 2680
- Differential equations and dynamical systems: APMA 1070, APMA 1180, APMA 1330, APMA 1360, APMA 1930P, APMA 1941G, APMA 2070, APMA 2190, APMA 2200, APMA 2550, APMA 2560, APMA 2570, APMA 2580B
- Scientific computing and optimization: APMA 1210, APMA 1160, APMA 1170, APMA 1180, APMA 1940Y, APMA 2070, APMA 2560, APMA 2580B, APMA 2580C
- Operations research: APMA 1200, APMA 1210
- Applications in biology: APMA 1070, APMA 1080, APMA 1930P, APMA 1930Y

4 APMA 0260 can substitute for the multivariable calculus and/or the linear algebra requirements. If it is used as a substitute for both requirements, then students must take one additional approved 1000-level APMA or MATH course not used elsewhere for concentration credit. APMA 1910, 1920, MATH 1090, 1910 are not allowed.

5 APMA 0330 or MATH 1110 may be used in place of APMA 0350. If MATH 1110 is used, then the concentration must include at least four 1000-level APMA courses (not including APMA 1910, 1920 or research/independent study courses). These can appear anywhere in the declaration.

6 APMA 0340 or MATH 1120 may be used in place of APMA 0360. If MATH 1120 is used, then the concentration must include at least four 1000-level APMA courses (not including APMA 1910, 1920 or research/independent study courses). These can appear anywhere in the declaration.

7 APMA 1910, 1920, MATH 1090, 1910 and research/independent study courses are not allowed. At most one of APMA 1001, MATH 1000, MATH 1001 can be used for concentration credit.

8 At most one of APMA 1650, APMA 1655, CSCI 1450, MATH 1210, MATH 1610 can be used for concentration credit.

9 At most one of CSCI 0300, CSCI 0330 can be used for concentration credit.

10 APMA 1655 is recommended. Higher-level courses in probability can satisfy this requirement with concentration advisor approval. The following courses are automatically approved: APMA 1080, APMA 1200, APMA 1660, APMA 1690, APMA 1710, APMA 1740/ APMA 2610, APMA 2630, APMA 2640.

11 Non-CSCI courses and arts, humanities, or social science CS courses cannot be used for concentration credit even if they are allowed as part of a pure CS concentration (currently CSCI 1250, 1280, 1360, 1370, 1800, 1805, 1870, 1952B, 1952X, 2002, 2952S).

12 The capstone can be one of the courses that completes the APMA pairing. Completing a capstone during the junior year might be allowed in exceptional cases for which completion during the senior year is impossible, such as the student's faculty research mentor not being on campus during the student's senior year, but this requires prior approval from the concentration advisor and the Director of Undergraduate Studies in CS. The following options can be used to satisfy this requirement:

- A pre-approved course that satisfies the APMA Sc.B. capstone requirement: currently APMA 1360, APMA 193*/194* (where * is any combination of numbers and letters; these are the APMA senior seminars).
- A directed research/independent study course from the APMA 1970/1971 series that is used for undergraduate research and is approved by the concentration advisor.
- Completion of a CS Sc.B. capstone as described in the CS Concentration Handbook at this link (https://cs.brown.edu/degrees/undergrad/concentrating-in-cs/concentration-handbook/). Usually, this involves taking one of the approved CS capstone courses at this link (https://cs.brown.edu/degrees/undergrad/concentrating-in-cs/concentration-requirements-2020/capstone/) and registering the capstone with the instructor of the course and with the CS department using the capstone registration form at this link (https://drive.google.com/file/d/1YYK7u4ccB0II52yxXiEI6sMwA7LZMrGy/view/). Depending on the course it may require the completion of an additional project.
- For students pursuing honors in APMA-CS, one of the two required semesters of independent study courses can be used to fulfill the capstone requirement.

Professional Tracks

The requirements for the professional tracks include all those of each of the standard tracks, as well as the following:

Students must complete full-time professional experiences doing work that is related to their concentration programs, totaling 2-6 months, whereby each internship must be at least one month in duration in cases where students choose to do more than one internship experience. Such work is normally done at a company, but may also be at a university under the supervision of a faculty member. Internships that take place between the end of the fall and the start of the spring semesters cannot be used to fulfill this requirement.

On completion of each professional experience, the student must write and upload to ASK a reflective essay about the experience, to be approved by the student's concentration advisor, addressing these questions:

- Which courses were put to use in your summer's work? Which topics, in particular, were important?

- In retrospect, which courses should you have taken before embarking on your summer experience? What are the topics from these courses that would have helped you over the summer if you had been more familiar with them?
- Are there topics you should have been familiar with in preparation for your summer experience, but are not taught at Brown? What are these topics?
- What did you learn from the experience that probably could not have been picked up from course work?
- Is the sort of work you did over the summer something you would like to continue doing once you graduate? Explain.
- Would you recommend your summer experience to other Brown students? Explain.

Honors

Concentrators that demonstrate excellence in grades and in undergraduate research can be awarded departmental honors. Honors students with primary advisors in Applied Math should follow the guidelines, requirements, and deadlines for honors as described in the bulletin for Applied Math concentrators (https://bulletin.brown.edu/the-college/concentrations/apma/) and as published on the APMA departmental website (https://appliedmath.brown.edu/academics/undergraduate-program/honors/). Honors students with primary advisors in Computer Science should follow the guidelines, requirements, and deadlines for honors as described in the bulletin for Computer Science concentrators (https://bulletin.brown.edu/the-college/concentrations/comp/) and as published on the CS departmental website (https://cs.brown.edu/degrees/undergrad/concentrating-in-cs/honors/). Students wishing to do honors research with a non-APMA or CS advisor should contact the Directors of Undergraduate Studies in APMA and CS to discuss options.

Applied Mathematics-Economics Concentration Requirements

The Applied Mathematics-Economics concentration is designed to reflect the mathematical and statistical nature of modern economic theory and empirical research. This concentration has two tracks. The first is the advanced economics track, which is intended to prepare students for graduate study in economics. The second is the mathematical finance track, which is intended to prepare students for graduate study in finance, or for careers in finance or financial engineering. Both tracks have A.B. degree versions and Sc.B. degree versions, as well as a Professional track option. If you are interested in declaring a concentration in Applied Mathematics-Economics, please refer to this page (https://economics.brown.edu/academics/undergraduate/concentrations/declaring/) for more information regarding the process.

Standard Program for the A.B. degree (Advanced Economics track):

Prerequisites:		
MATH 0100	Single Variable Calculus, Part II	
MATH 0520	Linear Algebra	
Course Requirements:		
Applied Mathematics Requirements		
(a) [1]		
APMA 0350 & APMA 0360	Applied Ordinary Differential Equations and Applied Partial Differential Equations I [2]	2
Select one of the following:		1
APMA 0160	Introduction to Scientific Computing (preferred)	
APMA 0200	Introduction to Modeling	
CSCI 0111	Computing Foundations: Data	
CSCI 0150	Introduction to Object-Oriented Programming and Computer Science	
CSCI 0170	Computer Science: An Integrated Introduction	
CSCI 0190	Accelerated Introduction to Computer Science	
Select one of the following:		1
APMA 1200	Operations Research: Probabilistic Models	
or APMA 1210	Operations Research: Deterministic Models	
Select one of the following:		1
APMA 1650	Statistical Inference I	
or APMA 1655	Honors Statistical Inference I	
(b) [1]		
Select one of the following:		1
APMA 1160	An Introduction to Numerical Optimization	
APMA 1180	Introduction to Numerical Solution of Differential Equations	
APMA 1200	Operations Research: Probabilistic Models	
APMA 1210	Operations Research: Deterministic Models	
APMA 1330	Applied Partial Differential Equations II	
APMA 1360	Applied Dynamical Systems	
APMA 1660	Statistical Inference II	
APMA 1690	Computational Probability and Statistics	
APMA 1670	Statistical Analysis of Time Series	
APMA 1680	Nonparametric Statistics	
APMA 1690	Computational Probability and Statistics	
APMA 1710	Information Theory	
APMA 1720	Monte Carlo Simulation with Applications to Finance	
APMA 1740	Recent Applications of Probability and Statistics	
APMA 1860	Graphs and Networks	
MATH 1010	Analysis: Functions of One Variable	
APMA 193X, 194X [6]	Senior Seminar series, depending on topic	
Economics Requirements:		**3**
ECON 1130	Intermediate Microeconomics (Mathematical) [3]	
ECON 1210	Intermediate Macroeconomics	
ECON 1630	Mathematical Econometrics I	
Two 1000-level courses from the "mathematical-economics" group: [4]		2
ECON 1170	Welfare Economics and Social Choice Theory	
ECON 1225	Advanced Macroeconomics: Monetary, Fiscal, and Stabilization Policies	
ECON 1255	Unemployment: Models and Policies	
ECON 1470	Bargaining Theory and Applications	
ECON 1490	Theory of Market Design	
ECON 1545	Topics in Macroeconomics, Development and International Economics	
ECON 1640	Mathematical Econometrics II	
ECON 1660	Big Data	
ECON 1670	Advanced Topics in Econometrics	
ECON 1680	Machine Learning, Text Analysis, and Economics	
ECON 1750	Investments II	
ECON 1770	Crisis Economics	
ECON 1805	Economics in the Laboratory	
ECON 1820	Theory of Behavioral Economics	
ECON 1860	The Theory of General Equilibrium	

ECON 1870	Game Theory and Applications to Economics	
One 1000-level course from the "data methods" group: [4]		1
ECON 1301	Economics of Education I	
ECON 1310	Labor Economics	
ECON 1315	Health, Education, and Social Policy	
ECON 1340	Economics of Global Warming	
ECON 1355	Environmental Issues in Development Economics	
ECON 1360	Health Economics	
ECON 1375	Inequality of Opportunity in the US	
ECON 1385	Intergenerational Poverty in America	
ECON 1400	The Economics of Mass Media	
ECON 1430	The Economics of Social Policy	
ECON 1510	Economic Development	
ECON 1520	Culture, History and Comparative Development	
ECON 1530	Health, Hunger and the Household in Developing Countries	
ECON 1629	Applied Research Methods for Economists	
ECON 1640	Mathematical Econometrics II	
ECON 1660	Big Data	
ECON 1670	Advanced Topics in Econometrics	
ECON 1680	Machine Learning, Text Analysis, and Economics	
ECON 1825	Behavioral Economics and Public Policy	
ECON 1830	Behavioral Finance	
One additional 1000-level economics course. [5]		1
Total Credits		**13**

1. No course may be used to simultaneously satisfy (a) and (b).
2. APMA 0330 and APMA 0340 may be substituted with advisor approval, but these are no longer being offered.
3. Or ECON 1110 with permission. For students matriculating at Brown in Fall 2021 or later, note that if ECON 1110 is used, then one additional course from the mathematical-economics group will be required
4. No course may be used to simultaneously satisfy the "mathematical economics," and "data methods" requirements.
5. Note that ECON 1620, ECON 1960, and ECON 1970 (independent study) cannot be used for concentration credit. However, 1620 and 1960 can be used for university credit and up to two 1970s may be used for university credit.
6. Requires written approval of the Director of Undergraduate Studies in Economics. APMA 1910 is not permitted.

Standard program for the Sc.B. degree (Advanced Economics track):

Prerequisites:		
MATH 0100	Single Variable Calculus, Part II	
MATH 0520	Linear Algebra	
Course Requirements:		
Applied Mathematics Requirements		
(a) [1]		
APMA 0350 & APMA 0360	Applied Ordinary Differential Equations and Applied Partial Differential Equations I [2]	2
Select one of the following:		1
APMA 0160	Introduction to Scientific Computing (preferred)	
APMA 0200	Introduction to Modeling	
CSCI 0111	Computing Foundations: Data	
CSCI 0190	Accelerated Introduction to Computer Science	
CSCI 0150	Introduction to Object-Oriented Programming and Computer Science	
CSCI 0170	Computer Science: An Integrated Introduction	
Select one of the following:		1
APMA 1200	Operations Research: Probabilistic Models	
or APMA 1210	Operations Research: Deterministic Models	
APMA 1650	Statistical Inference I	1
or APMA 1655	Honors Statistical Inference I	
(b) [1]		
Select two of the following:		2
APMA 1160	An Introduction to Numerical Optimization	
APMA 1180	Introduction to Numerical Solution of Differential Equations	
APMA 1200	Operations Research: Probabilistic Models	
APMA 1210	Operations Research: Deterministic Models	
APMA 1330	Applied Partial Differential Equations II	
APMA 1360	Applied Dynamical Systems	
APMA 1660	Statistical Inference II	
APMA 1670	Statistical Analysis of Time Series	
APMA 1680	Nonparametric Statistics	
APMA 1690	Computational Probability and Statistics	
APMA 1710	Information Theory	
APMA 1720	Monte Carlo Simulation with Applications to Finance	
APMA 1740	Recent Applications of Probability and Statistics	
APMA 1860	Graphs and Networks	
MATH 1010	Analysis: Functions of One Variable	
APMA 193X, 194X Senior Seminar series, depending on topic [6]		
Economics Requirements:		
ECON 1130	Intermediate Microeconomics (Mathematical) [3]	1
ECON 1210	Intermediate Macroeconomics	1
ECON 1630	Mathematical Econometrics I	1
Three 1000-level courses from the "mathematical-economics" group: [4]		3
ECON 1170	Welfare Economics and Social Choice Theory	
ECON 1225	Advanced Macroeconomics: Monetary, Fiscal, and Stabilization Policies	
ECON 1255	Unemployment: Models and Policies	
ECON 1470	Bargaining Theory and Applications	
ECON 1490	Theory of Market Design	
ECON 1545	Topics in Macroeconomics, Development and International Economics	
ECON 1640	Mathematical Econometrics II	
ECON 1660	Big Data	
ECON 1670	Advanced Topics in Econometrics	
ECON 1680	Machine Learning, Text Analysis, and Economics	
ECON 1750	Investments II	
ECON 1770	Crisis Economics	
ECON 1805	Economics in the Laboratory	
ECON 1820	Theory of Behavioral Economics	
ECON 1860	The Theory of General Equilibrium	

ECON 1870	Game Theory and Applications to Economics	
One 1000-level course from the "data methods" group: [4]		1
ECON 1301	Economics of Education I	
ECON 1310	Labor Economics	
ECON 1315	Health, Education, and Social Policy	
ECON 1340	Economics of Global Warming	
ECON 1355	Environmental Issues in Development Economics	
ECON 1360	Health Economics	
ECON 1375	Inequality of Opportunity in the US	
ECON 1385	Intergenerational Poverty in America	
ECON 1400	The Economics of Mass Media	
ECON 1430	The Economics of Social Policy	
ECON 1510	Economic Development	
ECON 1520	Culture, History and Comparative Development	
ECON 1530	Health, Hunger and the Household in Developing Countries	
ECON 1629	Applied Research Methods for Economists	
ECON 1640	Mathematical Econometrics II	
ECON 1660	Big Data	
ECON 1670	Advanced Topics in Econometrics	
ECON 1680	Machine Learning, Text Analysis, and Economics	
ECON 1825	Behavioral Economics and Public Policy	
ECON 1830	Behavioral Finance	
Two additional 1000-level economics courses [5]		2
Total Credits		**16**

1. No course may be used to simultaneously satisfy (a) and (b).
2. APMA 0330 and APMA 0340 may be substituted with advisor approval, but these are no longer being offered.
3. Or ECON 1110 with permission. For students matriculating at Brown in Fall 2021 or later, note that if ECON 1110 is used, then one additional course from the mathematical-economics group will be required
4. No course may be used to simultaneously satisfy the "mathematical economics" and "data methods" requirements.
5. Students may apply, at most, one Economics course whose number is in the range of 1000 to 1099 toward the concentration. Note that ECON 1620, ECON 1960, and ECON 1970 (independent study) cannot be used for concentration credit. However, 1620 and 1960 can be used for university credit and up to two 1970s may be used for university credit.
6. Requires written approval of the Director of Undergraduate Studies in Economics. APMA 1910 is not permitted.

Standard program for the A.B. degree (Mathematical Finance track):

Prerequisites:		
MATH 0100	Single Variable Calculus, Part II	
MATH 0520	Linear Algebra	
Course Requirements: 13 Courses: 6 Applied Math and 7 Economics		
Applied Mathematics Requirements		
(a)		
APMA 0350 & APMA 0360	Applied Ordinary Differential Equations and Applied Partial Differential Equations I [1]	2
Select one of the following:		1
APMA 0160	Introduction to Scientific Computing (preferred)	
APMA 0200	Introduction to Modeling	
CSCI 0111	Computing Foundations: Data	
CSCI 0150	Introduction to Object-Oriented Programming and Computer Science	
CSCI 0170	Computer Science: An Integrated Introduction	
CSCI 0190	Accelerated Introduction to Computer Science	
APMA 1200	Operations Research: Probabilistic Models	1
APMA 1650	Statistical Inference I	1
or APMA 1655	Honors Statistical Inference I	
(b)		
Select one of the following:		1
APMA 1160	An Introduction to Numerical Optimization	
APMA 1180	Introduction to Numerical Solution of Differential Equations	
APMA 1210	Operations Research: Deterministic Models	
APMA 1330	Applied Partial Differential Equations II	
APMA 1360	Applied Dynamical Systems	
APMA 1660	Statistical Inference II	
APMA 1670	Statistical Analysis of Time Series	
APMA 1680	Nonparametric Statistics	
APMA 1690	Computational Probability and Statistics	
APMA 1710	Information Theory	
APMA 1720	Monte Carlo Simulation with Applications to Finance (preferred)	
APMA 1740	Recent Applications of Probability and Statistics	
APMA 1860	Graphs and Networks	
MATH 1010	Analysis: Functions of One Variable	
APMA 193X, 194X Senior Seminar series, depending on topic [5]		
Economics Requirements:		
ECON 1130	Intermediate Microeconomics (Mathematical) [3]	1
ECON 1210	Intermediate Macroeconomics	1
ECON 1630	Mathematical Econometrics I	1
Select two 1000-level courses from the "financial economics" group: [2]		2
ECON 1710	Investments I	
ECON 1720	Corporate Finance	
ECON 1730	Venture Capital, Private Equity, and Entrepreneurship	
ECON 1750	Investments II	
ECON 1760	Financial Institutions	
ECON 1770	Crisis Economics	
ECON 1780	Advanced Topics in Corporate Finance	
ECON 1830	Behavioral Finance	
Select one 1000-level course from the "mathematical economics" group: [2]		1
ECON 1170	Welfare Economics and Social Choice Theory	
ECON 1225	Advanced Macroeconomics: Monetary, Fiscal, and Stabilization Policies	
ECON 1255	Unemployment: Models and Policies	
ECON 1470	Bargaining Theory and Applications	
ECON 1490	Theory of Market Design	
ECON 1545	Topics in Macroeconomics, Development and International Economics	
ECON 1640	Mathematical Econometrics II	

ECON 1660	Big Data	
ECON 1670	Advanced Topics in Econometrics	
ECON 1680	Machine Learning, Text Analysis, and Economics	
ECON 1750	Investments II	
ECON 1770	Crisis Economics	
ECON 1805	Economics in the Laboratory	
ECON 1820	Theory of Behavioral Economics	
ECON 1860	The Theory of General Equilibrium	
ECON 1870	Game Theory and Applications to Economics	
Select one 1000-level course from the "data methods" group: [2]		1
ECON 1301	Economics of Education I	
ECON 1310	Labor Economics	
ECON 1315	Health, Education, and Social Policy	
ECON 1340	Economics of Global Warming	
ECON 1355	Environmental Issues in Development Economics	
ECON 1360	Health Economics	
ECON 1375	Inequality of Opportunity in the US	
ECON 1385	Intergenerational Poverty in America	
ECON 1400	The Economics of Mass Media	
ECON 1430	The Economics of Social Policy	
ECON 1510	Economic Development	
ECON 1520	Culture, History and Comparative Development	
ECON 1530	Health, Hunger and the Household in Developing Countries	
ECON 1629	Applied Research Methods for Economists	
ECON 1640	Mathematical Econometrics II	
ECON 1660	Big Data	
ECON 1670	Advanced Topics in Econometrics	
ECON 1680	Machine Learning, Text Analysis, and Economics	
ECON 1825	Behavioral Economics and Public Policy	
ECON 1830	Behavioral Finance	
Total Credits		**13**

[1] APMA 0330 and APMA 0340 may be substituted with advisor approval, but these are no longer being offered.

[2] No course may be used to simultaneously satisfy any two or more of the "financial economics," "mathematical economics," and "data methods" requirements.

[3] Or ECON 1110 with permission. For students matriculating at Brown in Fall 2021 or later, note that if ECON 1110 is used, then one additional course from the mathematical-economics group will be required

[4] Note that ECON 1620, ECON 1960, and ECON 1970 (independent study) cannot be used for concentration credit. However, 1620 and 1960 can be used for university credit and up to two 1970s may be used for university credit.

[5] Requires written approval of the Director of Undergraduate Studies in Economics. APMA 1910 is not permitted.

Standard program for the Sc.B. degree (Mathematical Finance track):

Prerequisites:		
MATH 0100	Single Variable Calculus, Part II	
MATH 0520	Linear Algebra	
Course Requirements: 16 courses: 7 Applied Math and 9 Economics		
Applied Mathematics requirements:		
(a)		
APMA 0350 & APMA 0360	Applied Ordinary Differential Equations and Applied Partial Differential Equations I [1]	2
Select one of the following:		1
APMA 0160	Introduction to Scientific Computing (preferred)	
APMA 0200	Introduction to Modeling	
CSCI 0111	Computing Foundations: Data	
CSCI 0150	Introduction to Object-Oriented Programming and Computer Science	
CSCI 0170	Computer Science: An Integrated Introduction	
CSCI 0190	Accelerated Introduction to Computer Science	
APMA 1200	Operations Research: Probabilistic Models	1
APMA 1650	Statistical Inference I	1
or APMA 1655	Honors Statistical Inference I	
(b)		
Select two of the following:		2
APMA 1160	An Introduction to Numerical Optimization	
APMA 1180	Introduction to Numerical Solution of Differential Equations	
APMA 1210	Operations Research: Deterministic Models	
APMA 1330	Applied Partial Differential Equations II	
APMA 1360	Applied Dynamical Systems	
APMA 1660	Statistical Inference II	
APMA 1670	Statistical Analysis of Time Series	
APMA 1680	Nonparametric Statistics	
APMA 1690	Computational Probability and Statistics	
APMA 1710	Information Theory	
APMA 1720	Monte Carlo Simulation with Applications to Finance (preferred)	
APMA 1740	Recent Applications of Probability and Statistics	
APMA 1860	Graphs and Networks	
MATH 1010	Analysis: Functions of One Variable	
APMA 193X, 194X Senior Seminar series, depending on topic [5]		
Economics Requirements:		
ECON 1130	Intermediate Microeconomics (Mathematical) [3]	1
ECON 1210	Intermediate Macroeconomics	1
ECON 1630	Mathematical Econometrics I	1
Select three 1000-level courses from the "financial economics" group: [2]		3
ECON 1710	Investments I	
ECON 1720	Corporate Finance	
ECON 1730	Venture Capital, Private Equity, and Entrepreneurship	
ECON 1750	Investments II	
ECON 1760	Financial Institutions	
ECON 1770	Crisis Economics	
ECON 1780	Advanced Topics in Corporate Finance	
ECON 1830	Behavioral Finance	
Select two 1000-level courses from the "mathematical economics" group: [2]		2
ECON 1170	Welfare Economics and Social Choice Theory	
ECON 1225	Advanced Macroeconomics: Monetary, Fiscal, and Stabilization Policies	
ECON 1255	Unemployment: Models and Policies	

ECON 1470	Bargaining Theory and Applications	
ECON 1490	Theory of Market Design	
ECON 1545	Topics in Macroeconomics, Development and International Economics	
ECON 1640	Mathematical Econometrics II	
ECON 1660	Big Data	
ECON 1670	Advanced Topics in Econometrics	
ECON 1680	Machine Learning, Text Analysis, and Economics	
ECON 1750	Investments II	
ECON 1770	Crisis Economics	
ECON 1805	Economics in the Laboratory	
ECON 1820	Theory of Behavioral Economics	
ECON 1860	The Theory of General Equilibrium	
ECON 1870	Game Theory and Applications to Economics	
Select one 1000-level course from the "data methods" group: [2]		1
ECON 1301	Economics of Education I	
ECON 1310	Labor Economics	
ECON 1315	Health, Education, and Social Policy	
ECON 1340	Economics of Global Warming	
ECON 1355	Environmental Issues in Development Economics	
ECON 1360	Health Economics	
ECON 1375	Inequality of Opportunity in the US	
ECON 1385	Intergenerational Poverty in America	
ECON 1400	The Economics of Mass Media	
ECON 1430	The Economics of Social Policy	
ECON 1510	Economic Development	
ECON 1520	Culture, History and Comparative Development	
ECON 1530	Health, Hunger and the Household in Developing Countries	
ECON 1629	Applied Research Methods for Economists	
ECON 1640	Mathematical Econometrics II	
ECON 1660	Big Data	
ECON 1670	Advanced Topics in Econometrics	
ECON 1680	Machine Learning, Text Analysis, and Economics	
ECON 1825	Behavioral Economics and Public Policy	
ECON 1830	Behavioral Finance	
Total Credits		**16**

1 APMA 0330 and APMA 0340 may be substituted with advisor approval, but these are no longer being offered.

2 No course may be used to simultaneously satisfy any two or more of the "financial economics," "mathematical economics," and "data methods" requirements.

3 Or ECON 1110 with permission. For students matriculating at Brown in Fall 2021 or later, note that if ECON 1110 is used, then one additional course from the mathematical-economics group will be required

4 Note that ECON 1620, ECON 1960, and ECON 1970 (independent study) cannot be used for concentration credit. However, 1620 and 1960 can be used for university credit and up to two 1970s may be used for university credit.

5 Requires written approval of the Director of Undergraduate Studies in Economics. APMA 1910 is not permitted.

Honors

Applied Math-Economics concentrators who wish to pursue honors must find a primary faculty thesis advisor in either Economics or Applied Math. They will be held to the Honors requirements of their advisor's department. Joint concentrators in Applied Mathematics-Economics with an Economics thesis advisor should follow the requirements published here (https://economics.brown.edu/academics/undergraduate/honors-and-capstones/thesis/), while concentrators with an Applied Math thesis advisor should follow the requirements published here (https://www.brown.edu/academics/applied-mathematics/undergraduate-program/honors/).

Professional Track

The requirements for the professional track include all those of the standard track, as well as the following:

Students must complete full-time professional experiences doing work that is related to their concentration programs, totaling 2-6 months, whereby each internship must be at least one month in duration in cases where students choose to do more than one internship experience. Such work is normally done at a company, but may also be at a university under the supervision of a faculty member. Internships that take place between the end of the fall and the start of the spring semesters cannot be used to fulfill this requirement.

On completion of each professional experience, the student must write and upload to ASK a reflective essay about the experience, to be approved by the student's concentration advisor.

- Which courses were put to use in your summer's work? Which topics, in particular, were important?
- In retrospect, which courses should you have taken before embarking on your summer experience? What are the topics from these courses that would have helped you over the summer if you had been more familiar with them?
- Are there topics you should have been familiar with in preparation for your summer experience, but are not taught at Brown? What are these topics?
- What did you learn from the experience that probably could not have been picked up from course work?
- Is the sort of work you did over the summer something you would like to continue doing once you graduate? Explain.
- Would you recommend your summer experience to other Brown students? Explain.

Applied Mathematics Graduate Program

The department of Applied Mathematics offers graduate programs leading to the Master of Science (Sc.M.) degree and the Doctor of Philosophy (Ph.D.) degree.

For more information on admission and program requirements, please visit the following website:

http://www.brown.edu/academics/gradschool/programs/applied-mathematics (http://www.brown.edu/academics/gradschool/programs/applied-mathematics/)

Courses

APMA 0070. Introduction to Applied Complex Variables.
Applications of complex analysis that do not require calculus as a prerequisite. Topics include algebra of complex numbers, plane geometry by means of complex coordinates, complex exponentials, and logarithms and their relation to trigonometry, polynomials, and roots of polynomials, conformal mappings, rational functions and their applications, finite Fourier series and the FFT, iterations and fractals. Uses MATLAB, which has easy and comprehensive complex variable capabilities.

APMA 0090. Introduction to Mathematical Modeling.
We will explore issues of mathematical modeling and analysis. Five to six self-contained topics will be discussed and developed. The course will include seminars in which modeling issues are discussed, lectures to provide mathematical background, and computational experiments. Required mathematical background is knowledge of one-variable calculus, and no prior computing experience will be assumed.

APMA 0100. Elementary Probability for Applications.
This course serves as an introduction to probability and stochastic processes with applications to practical problems. It will cover basic probability and stochastic processes such as basic concepts of probability and conditional probability, simple random walk, Markov chains, continuous distributions, Brownian motion and option pricing. Enrollment limited to 19 first year students.

APMA 0110. What's the big deal with Data Science?.
This seminar serves as a practical introduction to the interdisciplinary field of data science. Over the course of the semester, students will be exposed to the diversity of questions that data science can address by reading current scholarly works from leading researchers. Through hands-on labs and experiences, students will gain facility with computational and visualization techniques for uncovering meaning from large numerical and text-based data sets. Ultimately, students will gain fluency with data science vocabulary and ideas. There are no prerequisites for this course.

APMA 0111. Data Science and Social Justice.
This first-year seminar explores the impact of data and algorithms on equity and justice. Data analysis and visualization can help identify inequities and advocate for social justice. At the same time, data-based algorithms can institutionalize and rationalize unfair practices and injustices. In this course, we will engage with fundamental questions about the role of data to work towards social justice. We will gain introductory data science skills, discuss algorithmic bias, equity, and fairness, and work with real-world data sets and algorithms to examine inequities in health, policing, prisons, and welfare. Everybody is welcome - no prerequisites are needed.

Spr	APMA0111	S01	26025	MWF	10:00-10:50(03)	'To Be Arranged'

APMA 0120. Mathematics of Finance.
The current volatility in international financial markets makes it imparative for us to become competent in financial calculations early in our liberal arts and scientific career paths. This course is designed to prepare the student with those elements of mathematics of finance appropriate for the calculations necessary in financial transactions.

APMA 0160. Introduction to Scientific Computing.
For students in any discipline that may involve numerical computations. Includes instruction for programming in MATLAB. Applications discussed include solution of linear equations (with vectors and matrices) and nonlinear equations (by bisection, iteration, and Newton's method), interpolation, and curve-fitting, difference equations, iterated maps, numerical differentiation and integration, and differential equations. Prerequisites: MATH 0100 or equivalent.

Fall	APMA0160	S01	17762	MWF	1:00-1:50(08)	(P. Sentz)

APMA 0180. Modeling the World with Mathematics: An Introduction for Non-Mathematicians.
Mathematics is the foundation of our technological society and most of its powerful ideas are quite accessible. This course will explain some of these using historical texts and Excel. Topics include the predictive power of 'differential equations' from the planets to epidemics, oscillations and music, chaotic systems, randomness and the atomic bomb. Prerequisite: some knowledge of calculus.

APMA 0200. Introduction to Modeling.
This course provides an introduction to the mathematical modeling of selected biological, chemical, engineering, and physical processes. The goal is to illustrate the typical way in which applied mathematicians approach practical applications, from understanding the underlying problem, creating a model, analyzing the model using mathematical techniques, and interpreting the findings in terms of the original problem. Single-variable calculus is the only requirement; all other techniques from differential equations, linear algebra, and numerical methods, to probability and statistics will be introduced in class. Prerequisites: Math 0100 or equivalent.

Fall	APMA0200	S01	17535	MWF	1:00-1:50(08)	(J. Darbon)

APMA 0260. Linear Algebra and Multivariable Calculus for Applied Mathematics.
This one-semester course provides an integrated introduction to multi-variable calculus and linear algebra. Students will develop a strong foundation in mathematical concepts and techniques essential for the applied mathematics concentration.

Spr	APMA0260	S01	26311	MWF	2:00-2:50(07)	(P. Tabrizian)

APMA 0330. Methods of Applied Mathematics I.
This course will cover mathematical techniques involving ordinary differential equations used in the analysis of physical, biological, and economic phenomena. The course emphasizes the use of established methods in applications rather than rigorous foundation. Topics include: first and second order differential equations, an introduction to numerical methods, series solutions, and Laplace transformations. Prerequisites: MATH 0100 or equivalent.

APMA 0340. Methods of Applied Mathematics II.
This course will cover mathematical techniques involving ordinary and partial differential equations and statistics used in the analysis of physical, biological, and economic phenomena. The course emphasizes the use of established methods rather than rigorous foundations. Topics include: applications of linear algebra to systems of equations; numerical methods; nonlinear problems and stability; introduction to partial differential equations; introduction to statistics. Prerequisites: APMA 0330 or equivalent.

APMA 0350. Applied Ordinary Differential Equations.
This course provides a comprehensive introduction to ordinary differential equations and their applications. During the course, we will see how applied mathematicians use ordinary differential equations to solve practical applications, from understanding the underlying problem, creating a differential-equations model, solving the model using analytical, numerical, or qualitative methods, and interpreting the findings in terms of the original problem. We will also learn about the underlying rigorous theoretical foundations of differential equations. Prerequisites: MATH 0100 or equivalent; knowledge of matrix-vector operations, determinants, and linear systems.

Fall	APMA0350	S01	17536	MWF	9:00-9:50(09)	(P. Tabrizian)
Fall	APMA0350	S02	17537	MWF	12:00-12:50(15)	(K. Mallory)
Spr	APMA0350	S01	26026	MWF	12:00-12:50(01)	(Z. Yang)

APMA 0360. Applied Partial Differential Equations I.
This course provides an introduction to partial differential equations and their applications. We will learn how to use partial differential equations to solve problems that arise in practical applications, formulating questions about a real-world problem, creating a partial differential equation model that can help answer these questions, solving the resulting system using analytical, numerical, and qualitative methods, and interpreting the results in terms of the original application. To help us support and justify our approaches and solutions, we will also learn about theoretical foundations of partial differential equations. Prerequisites: APMA 0350 or equivalent.

Fall	APMA0360	S01	17538	MWF	12:00-12:50(15)	(P. Tabrizian)
Spr	APMA0360	S01	26027	MWF	12:00-12:50(01)	(P. Tabrizian)
Spr	APMA0360	S02	26028	TTh	10:30-11:50(09)	(H. Dong)

APMA 0410. Mathematical Methods in the Brain Sciences.
Basic mathematical methods commonly used in the neural and cognitive sciences. Topics include: introduction to probability and statistics, emphasizing hypothesis testing and modern nonparametric methods; introduction to differential equations and systems of differential equations, emphasizing qualitative behavior and simple phase-plane analysis. Examples from neuroscience, cognitive science, and other sciences. Prerequisite: MATH 0100 or equivalent.

APMA 0650. Essential Statistics.
A first course in probability and statistics emphasizing statistical reasoning and basic concepts. Topics include visual and numerical summaries of data, representative and non-representative samples, elementary discrete probability theory, the normal distribution, sampling variability, elementary statistical inference, measures of association. Examples and applications from the popular press and the life, social and physical sciences. Not calculus-based. No prerequisites.

Spr	APMA0650	S01	26029	TTh	1:00-2:20(08)	(A. Culiuc)

APMA 1070. Quantitative Models of Biological Systems.
Quantitative dynamic models help understand problems in biology and there has been rapid progress in recent years. This course provides an introduction to the concepts and techniques, with applications to population dynamics, infectious diseases, enzyme kinetics, and cellular biology. Additional topics covered will vary. Mathematical techniques will be discussed as they arise in the context of biological problems. Prerequisites: APMA 0350 or equivalent.

Spr	APMA1070	S01	26030	MWF	11:00-11:50(04)	(A. Culiuc)

APMA 1080. Inference in Genomics and Molecular Biology.
This course is an introduction to the probabilistic and statistical models that have found widespread use in genomics and molecular biology. The emphasis is on foundational models and ideas rather than practical application. Likely topics include Markov chains, hidden Markov models, directed graphical models, mixture models, linear regression, regularization, dimensionality reduction, clustering, Bayesian inference, and multiple hypothesis testing. Examples will focus on the connection to genomics and molecular biology, but all of these tools have found widespread use in a variety of disciplines. Mathematical and computational exercises will reinforce the topics presented in lecture. Prerequisites: APMA 1650 or equivalent; MATH 520 or equivalent; APMA 0160 or CSCI 0111 or equivalent.

Fall	APMA1080	S01	17539	MWF	10:00-10:50(14)	(M. Harrison)

APMA 1150. Machine Learning for Scientific Modeling: Data-Driven Discovery of Differential Equations(MATH 1150).
Interested students must register for MATH 1150.

APMA 1160. An Introduction to Numerical Optimization.
This course provides a thorough introduction to numerical methods and algorithms for solving non-linear continuous optimization problems. A particular attention will be given to the mathematical underpinnings to understand the theoretical properties of the optimization problems and the algorithms designed to solve them. Topics will include: line search methods, trust-region methods, nonlinear conjugate gradient methods, an introduction to constrained optimization (Karush-Kuhn-Tucker conditions, mini-maximization, saddle-points of Lagrangians). Some applications in signal and image processing will be explored. Prerequisites: MATH 0180 or equivalent; MATH 0520 or equivalent; APMA 0160 or CSCI 0111 or equivalent. APMA 1170 or equivalent is recommended.

Spr	APMA1160	S01	26031	MWF	9:00-9:50(04)	(J. Darbon)

APMA 1170. Introduction to Computational Linear Algebra.
Focuses on fundamental algorithms in computational linear algebra with relevance to all science concentrators. Basic linear algebra and matrix decompositions (Cholesky, LU, QR, etc.), round-off errors and numerical analysis of errors and convergence. Iterative methods and conjugate gradient techniques. Computation of eigenvalues and eigenvectors, and an introduction to least squares methods. Prerequisites: MATH 0100 or equivalent; MATH 0520 or equivalent. Experience with a programming language is strongly recommended.

Fall	APMA1170	S01	17540	MWF	9:00-9:50(09)	(D. Kim)

APMA 1180. Introduction to Numerical Solution of Differential Equations.
Fundamental numerical techniques for solving ordinary and partial differential equations. Overview of techniques for approximation and integration of functions. Development of multi-step and multi-stage methods, error analysis, step-size control for ordinary differential equations. Solution of two-point boundary value problems, introduction to methods for solving linear partial differential equations. Students will be required to use Matlab (or other computer languages) to implement the mathematical algorithms under consideration: experience with a programming language is therefore strongly recommended. Prerequisites: APMA 0350 or equivalent; APMA 0360 or equivalent.

Spr	APMA1180	S01	26032	MWF	1:00-1:50(06)	(P. Sentz)

APMA 1190. Finite Volume Method for CFD: A Survey.
This course will provide students with an overview of the subjects necessary to perform robust simulations of computational fluid dynamics (CFD) problems. After an initial overview of the finite volume method and fluid mechanics, students will use the finite volume library OpenFOAM to explore the different components that make up a modern CFD code (discretization, linear algebra, timestepping, boundary conditions, splitting schemes, and multiphysics) and learn how to navigate a production scale software library.

APMA 1200. Operations Research: Probabilistic Models.
APMA 1200 serves as an introduction to stochastic processes and stochastic optimization. After a review of basic probability theory, including conditional probability and conditional expectations, topics covered will include discrete-time Markov chains, exponential distributions, Poisson processes and continuous-time Markov chains, elementary queueing theory, martingales, Markov decision processes and dynamic programming. If time permits topics selected from filtering of hidden Markov chains, renewal processes, and Brownian motion could be included. Prerequisites: APMA 1650 (or equivalent) and MATH 520 (or equivalent). The course assumes calculus, basic probability theory, and linear algebra.

Spr	APMA1200	S01	26033	MWF	11:00-11:50(04)	(H. Wang)

APMA 1210. Operations Research: Deterministic Models.
An introduction to the basic mathematical ideas and computational methods of optimizing allocation of effort or resources, with or without constraints. Linear programming, network models, dynamic programming, and integer programming. Prerequisites: MATH 0100 or equivalent; MATH 520 or equivalent; APMA 0160 or CSCI 0111 or equivalent.

Fall	APMA1210	S01	17541	TTh	10:30-11:50(13)	(A. Culiuc)

APMA 1250. Advanced Engineering Mechanics (ENGN 1370).
Interested students must register for ENGN 1370.

APMA 1260. Introduction to the Mechanics of Solids and Fluids.
An introduction to the dynamics of fluid flow and deforming elastic solids for students in the physical or mathematical sciences. Topics in fluid mechanics include statics, simple viscous flows, inviscid flows, potential flow, linear water waves, and acoustics. Topics in solid mechanics include elastic/plastic deformation, strain and stress, simple elastostatics, and elastic waves with reference to seismology. Offered in alternate years.

APMA 1330. Applied Partial Differential Equations II.
Review of vector calculus and curvilinear coordinates. Partial differential equations. Heat conduction and diffusion equations, the wave equation, Laplace and Poisson equations. Separation of variables, special functions, Fourier series and power series solution of differential equations. Sturm-Liouville problem and eigenfunction expansions. Prerequisites: APMA 0360 or equivalent.

Fall	APMA1330	S01	17542	TTh	9:00-10:20(05)	(Z. Yang)

APMA 1340. Methods of Applied Mathematics III, IV.
See Methods Of Applied Mathematics III, IV (APMA 1330) for course description.

APMA 1360. Applied Dynamical Systems.
This course gives an overview of the theory and applications of dynamical systems modeled by differential equations and maps. We will discuss changes of the dynamics when parameters are varied, investigate periodic and homoclinic solutions that arise in applications, and study the impact of additional structures such as time reversibility and conserved quantities on the dynamics. We will also study systems with complicated "chaotic" dynamics that possess attracting sets which do not have an integer dimension. Applications to chemical reactions, climate, epidemiology, and phase transitions will be discussed. Prerequisites: APMA 0350 or equivalent.

Spr	APMA1360	S01	26034	MWF	9:00-9:50(02)	(B. Sandstede)

APMA 1650. Statistical Inference I.
APMA 1650 is an integrated first course in mathematical statistics. The first half of APMA 1650 covers probability and the last half is statistics, integrated with its probabilistic foundation. Specific topics include probability spaces, discrete and continuous random variables, methods for parameter estimation, confidence intervals, and hypothesis testing. Prerequisites: MATH 0100 or equivalent.

Fall	APMA1650	S01	17543	MWF	2:00-2:50(01)	(A. Culiuc)
Fall	APMA1650	S02	17765	MWF	10:00-10:50(14)	'To Be Arranged'
Spr	APMA1650	S01	26035	MWF	9:00-9:50(02)	'To Be Arranged'
Spr	APMA1650	S02	26036	MWF	10:00-10:50(03)	'To Be Arranged'

APMA 1655. Honors Statistical Inference I.
Students may opt to enroll in APMA 1655 for more in depth coverage of APMA 1650. Enrollment in 1655 will include an optional recitation section and required additional individual work. Applied Math concentrators are encouraged to take 1655. Prerequisites: MATH 0180 or equivalent.

Fall	APMA1655	S01	17544	MWF	11:00-11:50(16)	'To Be Arranged'
Spr	APMA1655	S01	26037	TTh	2:30-3:50(11)	(A. Vander Werf)

APMA 1660. Statistical Inference II.
APMA 1660 is designed as a sequel to APMA 1650 to form one of the alternative tracks for an integrated year's course in mathematical statistics. The main topic is linear models in statistics. Specific topics include likelihood-ratio tests, nonparametric tests, introduction to statistical computing, matrix approach to simple-linear and multiple regression, analysis of variance, and design of experiments. Prerequisites: APMA 1650 or equivalent; MATH 0520 or equivalent.

Spr	APMA1660	S01	26038	MWF	10:00-10:50(03)	(K. Meng)

APMA 1670. Statistical Analysis of Time Series.
Time series analysis is an important branch of mathematical statistics with many applications to signal processing, econometrics, geology, etc. The course emphasizes methods for analysis in the frequency domain, in particular, estimation of the spectrum of time-series, but time domain methods are also covered. Prerequisites: elementary probability and statistics on the level of APMA 1650-1660.

APMA 1680. Nonparametric Statistics.
A systematic treatment of distribution-free alternatives to classical statistical tests. These nonparametric tests make minimum assumptions about distributions governing the generation of observations, yet are of nearly equal power to the classical alternatives. Prerequisite: APMA 1650 or equivalent. Offered in alternate years.

APMA 1681. Computational Neuroscience (NEUR 1680).
Interested students must register for NEUR 1680.

APMA 1690. Computational Probability and Statistics.
Examination of probability theory and mathematical statistics from the perspective of computing. Topics selected from random number generation, Monte Carlo methods, limit theorems, stochastic dependence, Bayesian networks, dimensionality reduction. Prerequisites: APMA 1650 or equivalent; programming experience is recommended.

Fall	APMA1690	S01	17545	TTh	1:00-2:20(06)	(K. Meng)

APMA 1700. The Mathematics of Insurance.
The course consists of two parts: the first treats life contingencies, i.e. the construction of models for individual life insurance contracts. The second treats the Collective Theory of Risk, which constructs mathematical models for the insurance company and its portfolio of policies as a whole. Suitable also for students proceeding to the Institute of Actuaries examinations. Prerequisites: Probability Theory to the level of APMA 1650 or MATH 1610.

APMA 1710. Information Theory.
Information theory is the study of the fundamental limits of information transmission and storage. This course, intended primarily for advanced undergraduates and beginning graduate students, offers a broad introduction to information theory and its applications: Entropy and information, lossless data compression, communication in the presence of noise, channel capacity, channel coding, source-channel separation, lossy data compression. Prerequisites: APMA 1650 or equivalent.

Spr	APMA1710	S01	26039	TTh	10:30-11:50(09)	(P. Dupuis)

APMA 1720. Monte Carlo Simulation with Applications to Finance.
The course will cover the basics of Monte Carlo and its applications to financial engineering: generating random variables and simulating stochastic processes; analysis of simulated data; variance reduction techniques; binomial trees and option pricing; Black-Scholes formula; portfolio optimization; interest rate models. The course will use MATLAB as the standard simulation tool. Prerequisites: APMA 1650 or MATH 1210/1610

APMA 1740. Recent Applications of Probability and Statistics.
This course develops the mathematical foundations of modern applications of statistics to the computational, cognitive, engineering, and neural sciences. The course is rigorous, but the emphasis is on application. Topics include: Gibbs ensembles and their relation to maximum entropy, large deviations, exponential models, and information theory; statistical estimation and classification; graphical models, dynamic programming, MCMC, parameter estimation, and the EM algorithm. Graduate version: 2610; Undergraduate version: 1740. Prerequisites: APMA 1650 or equivalent; programming experience; strong mathematics background. APMA 1200 or APMA 1690 or similar courses recommended. MATH 1010 or equivalent is recommended for APMA 2610.

Spr	APMA1740	S01	26040	MWF	2:00-2:50(07)	(O. Nguyen)

APMA 1850. Introdution to High Performance Parallel Computing.
No description available.

APMA 1860. Graphs and Networks.
Selected topics about the mathematics of graphs and networks with an emphasis on random graph models and the dynamics of processes operating on these graphs. Topics include: empirical properties of biological, social, and technological networks (small-world effects, scale-free properties, transitivity, community structure); mathematical and statistical models of random graphs and their properties (Bernoulli random graphs, preferential attachment models, stochastic block models, phase transitions); dynamical processes on graphs and networks (percolation, cascades, epidemics, queuing, synchronization). Prerequisites: MATH 520 or equivalent; APMA 0350 or equivalent; APMA 1650 or equivalent; programming experience. APMA 1200 or APMA 1690 or similar courses recommended.

Fall	APMA1860	S01	17546	TTh	9:00-10:20(05)	(A. Vander Werf)

APMA 1880. Advanced Matrix Theory.
Canonical forms of orthogonal, Hermitian and normal matrices: Rayleigh quotients. Norms, eigenvalues, matrix equations, generalized inverses. Banded, sparse, non-negative and circulant matrices. Prerequisite: APMA 0340 or 0360, or MATH 0520 or 0540, or permission of the instructor.

APMA 1910. Race and Gender in the Scientific Community.
This course examines the (1) disparities in representation in the scientific community, (2) issues facing different groups in the sciences, and (3) paths towards a more inclusive scientific environment. We will delve into the current statistics on racial and gender demographics in the sciences and explore their background through texts dealing with the history, philosophy, and sociology of science. We will also explore the specific problems faced by underrepresented and well-represented racial minorities, women, and LGBTQ community members. The course is reading intensive and discussion based. To be added to the waitlist for this course, please go to https://goo.gl/forms/foK0fyGxm5Eu2irA2

Fall	APMA1910	S01	17764	TTh	2:30-3:50(12)	(K. Mallory)

APMA 1911. Race and Gender in the Scientific Community (MATH 1910).
Interested students must register for MATH 1910.

APMA 1930A. Actuarial Mathematics.
A seminar considering selected topics from two fields: (1) life contingencies-the study of the valuation of life insurance contracts; and (2) collective risk theory, which is concerned with the random process that generates claims for a portfolio of policies. Topics are chosen from *Actuarial Mathematics*, 2nd ed., by Bowers, Gerber, Hickman, Jones, and Nesbitt. Prerequisite: knowledge of probability theory to the level of APMA 1650 or MATH 1610. Particularly appropriate for students planning to take the examinations of the Society of Actuaries.

APMA 1930B. Computational Probability and Statistics.
Examination of probability theory and mathematical statistics from the perspective of computing. Topics selected from: random number generation, Monte Carlo methods, limit theorems, stochastic dependence, Bayesian networks, probabilistic grammars.

APMA 1930C. Information Theory.
Information theory is the mathematical study of the fundamental limits of information transmission (or coding) and storage (or compression). This course offers a broad introduction to information theory and its real-world applications. A subset of the following is covered: entropy and information; the asymptotic equipartition property; theoretical limits of lossless data compression and practical algorithms; communication in the presence of noise-channel coding, channel capacity; source-channel separation; Gaussian channels; Lossy data compression.

APMA 1930D. Mixing and Transport in Dynamical Systems.
Mixing and transport are important in several areas of applied science, including fluid mechanics, atmospheric science, chemistry, and particle dynamics. In many cases, mixing seems highly complicated and unpredictable. We use the modern theory of dynamical systems to understand and predict mixing and transport from the differential equations describing the physical process in question. Prerequisites: APMA 0330, 0340; or APMA 0350, 0360.

APMA 1930E. Ocean Dynamics.
Works through the popular book by Henry Stommel entitled *A View of the Sea.* Introduces the appropriate mathematics to match the physical concepts introduced in the book.

APMA 1930G. The Mathematics of Sports.
Topics to be discussed will range from the determination of who won the match, through biomechanics, free-fall of flexible bodies and aerodynamics, to the flight of ski jumpers and similar unnatural phenomena. Prerequisite: APMA 0340 or equivalent, or permission of the instructor.

APMA 1930H. Scaling and Self-Similarity.
The themes of scaling and self-similarity provide the simplest, and yet the most fruitful description of complicated forms in nature such as the branching of trees, the structure of human lungs, rugged natural landscapes, and turbulent fluid flows. This seminar is an investigation of some of these phenomena in a self-contained setting requiring little more mathematical background than high school algebra.

Topics to be covered: Dimensional analysis; empirical laws in biology, geosciences, and physics and the interplay between scaling and function; an introduction to fractals; social networks and the "small world" phenomenon.

APMA 1930I. Random Matrix Theory.
In the past few years, random matrices have become extremely important in a variety of fields such as computer science, physics and statistics. They are also of basic importance in various areas of mathematics. This class will serve as an introduction to this area. The focus is on the basic matrix ensembles and their limiting distributions, but several applications will be considered. Prerequisites: MATH 0200 or 0350; and MATH 0520 or 0540; and APMA 0350, 0360, 1650, and 1660. APMA 1170 and MATH 1010 are recommended, but not required.

APMA 1930J. Mathematics of Random Networks.
An intro to the emerging field of random networks and a glimpse of some of the latest developments. Random networks arise in a variety of applications including statistics, communications, physics, biology and social networks. They are studied using methods from a variety of disciplines ranging from probability, graph theory and statistical physics to nonlinear dynamical systems. Describes elements of these theories and shows how they can be used to gain practical insight into various aspects of these networks including their structure, design, distributed control and self-organizing properties. Prerequisites: Advanced calculus, basic knowledge of probability. Enrollment limited to 40.

APMA 1930M. Applied Asymptotic Analysis.
Many problems in applied mathematics and physics are nonlinear and are intractable to solve using elementary methods. In this course we will systematically develop techniques for obtaining quantitative information from nonlinear systems by exploiting small scale parameters. Topics will include: regular and singular perturbations, boundary layer theory, multiscale and averaging methods and asymptotic expansions of integrals. Along the way, we will discuss many applications including nonlinear waves, coupled oscillators, nonlinear optics, fluid dynamics and pattern formation.

APMA 1930P. Mathematics and Climate.
Mathematical models play a critical role in projecting and understanding climate processes. This course will discuss techniques for application of theoretical models, computational experiments, and data analysis in climate science, including oceanic, atmospheric, and ecological phenomena. Intended for students in applied mathematics and other concentrations with quantitative skills who are interested in applying their knowledge to mathematical modeling and climate problems. No previous coursework in climate science is required. Physical science concepts and mathematical techniques will be introduced throughout the course. Students will develop collaborative or individual projects later in the semester. Prerequisites: APMA 0360, or APMA 0340, or written permission; APMA 1650 is recommended.

Spr	APMA1930F	S01	26232	TTh	9:00-10:20(05)	(M. Freilich)

APMA 1930U. Introduction to Stochastic Differential Equations.
This seminar course serves as an introduction to stochastic differential equations at the senior undergraduate level. Topics covered include Brownian motion and white noise, stochastic integrals, the Itô calculus, existence and uniqueness of solutions to Itô stochastic differential equations, and the Feynman-Kac formula. More advanced topics, such as fractional Brownian motion, Lévy processes, and stochastic control theory, may be addressed depending on the interests of the class and time restrictions.

APMA 1930W. Probabilities in Quantum Mechanics.
We will start from scratch. We will be rigorous, while making a careful accounting of the (surprisingly few) conceptual assumptions that lead inexorably to consequences that are almost impossible to believe. With an eye on some of the most startling and vexing of these, we will construct a minimum mathematical foundation sufficient to explore: the abrupt transition from the weird quantum to the familiar classical world; the uncertainty principles; teleportation; Bell’s theorem and the Einstein-Bohr debates; quantum erasure; the Conway-Kochen “free-will theorem”; (unbreakable) quantum encryption, and, an introduction to quantum computing.

Spr	APMA1930V	S01	26049	MWF	1:00-1:50(06)	(S. Geman)

APMA 1930X. Probability, Optimization, and Stochastic Calculus.
This senior seminar will explore various topics in probability, including stochastic processes, stochastic optimization including optimal stopping and optimal stochastic control, Brownian motion, stochastic calculus, connection to partial differential equations, and some of their applications. The class format will involve both lectures and class discussions. Calculus based undergraduate probability, such as APMA 1650/1655 or MATH 1210/1610, is required. Minimal experience in MATLAB is recommended, but not required.

Fall	APMA1930X	S01	18905	MWF	11:00-11:50(16)	(H. Wang)

APMA 1930Z. Introduction to Mathematical Machine Learning.
This course will provide an introduction to machine learning from a mathematical perspective. The primary objective of this course is to equip students with the skills to ask mathematical questions when studying machine learning algorithms. Classical supervised learning methods will be presented and studied using the tools from information theory, statistical learning theory, optimization, and basic functional analysis. The course will cover three categories of machine learning approaches: linear methods, kernel-based methods, and deep learning methods, each applied to regression, classification, and dimension reduction. Coding exercises will be an essential part of the course to empirically study strengths and weakness of methods.

Fall	APMA1930Z	S01	18628	MWF	2:00-2:50(01)	(P. Dupuis)

APMA 1940A. Coding and Information Theory.
In a host of applications, from satellite communication to compact disc technology, the storage, retrieval, and transmission of digital data relies upon the theory of coding and information for efficient and error-free performance. This course is about choosing representations that minimize the amount of data (compression) and the probability of an error in data handling (error-correcting codes). Prerequisite: A knowledge of basic probability theory at the level of APMA 1650 or MATH 1610.

APMA 1940B. Information and Coding Theory.
Originally developed by C.E. Shannon in the 1940s for describing bounds on information rates across telecommunication channels, information and coding theory is now employed in a large number of disciplines for modeling and analysis of problems that are statistical in nature. This course provides a general introduction to the field. Main topics include entropy, error correcting codes, source coding, data compression. Of special interest will be the connection to problems in pattern recognition. Includes a number of projects relevant to neuroscience, cognitive and linguistic sciences, and computer vision. Prerequisites: High school algebra, calculus. MATLAB or other computer experience helpful. Prior exposure to probability theory/statistics helpful.

APMA 1940C. Introduction to Mathematics of Fluids.
Equations that arise from the description of fluid motion are born in physics, yet are interesting from a more mathematical point of view as well. Selected topics from fluid dynamics introduce various problems and techniques in the analysis of partial differential equations. Possible topics include stability, existence and uniqueness of solutions, variational problems, and active scalar equations. No prior knowledge of fluid dynamics is necessary.

APMA 1940D. Iterative Methods.
Large, sparse systems of equations arise in many areas of mathematical application and in this course we explore the popular numerical solution techniques being used to efficiently solve these problems. Throughout the course we will study preconditioning strategies, Krylov subspace acceleration methods, and other projection methods. In particular, we will develop a working knowledge of the Conjugate Gradient and Minimum Residual (and Generalized Minimum Residual) algorithms. Multigrid and Domain Decomposition Methods will also be studied as well as parallel implementation, if time permits.

APMA 1940E. Mathematical Biology.
This course is designed for undergraduate students in mathematics who have an interest in the life sciences. No biological experience is necessary, as we begin by a review of the relevant topics. We then examine a number of case studies where mathematical tools have been successfully applied to biological systems. Mathematical subjects include differential equations, topology and geometry.

APMA 1940F. Mathematics of Physical Plasmas.
Plasmas can be big, as in the solar wind, or small, as in fluorescent bulbs. Both kinds are described by the same mathematics. Similar mathematics describes semiconducting materials, the movement of galaxies, and the re-entry of satellites. We consider how all of these physical systems are described by certain partial differential equations. Then we invoke the power of mathematics. The course is primarily mathematical. Prerequisites: APMA 0340 or 0360, MATH 0180 or 0200 or 0350, and PHYS 0060 or PHYS 0080 or ENGN 0510.

APMA 1940G. Multigrid Methods.
Mulitgrid methods are a very active area of research in Applied Mathematics. An introduction to these techniques will expose the student to cutting-edge mathematics and perhaps pique further interest in the field of scientific computation.

APMA 1940H. Numerical Linear Algebra.
This course will deal with advanced concepts in numerical linear algebra. Among the topics covered: Singular Value Decompositions (SVD) QR factorization, Conditioning and Stability and Iterative Methods.

APMA 1940I. The Mathematics of Finance.
The mathematics of speculation as reflected in the securities and commodities markets. Particular emphasis placed on the evaluation of risk and its role in decision-making under uncertainty. Prerequisite: basic probability.

APMA 1940J. The Mathematics of Speculation.
The course will deal with the mathematics of speculation as reflected in the securities and commodities markets. Particular emphasis will be placed on the evaluation of risk and its role in decision making under uncertainty. Prerequisite: basic probability.

APMA 1940K. Fluid Dynamics and Physical Oceanography.
Introduction to fluid dynamics as applied to the mathematical modeling and simulation of ocean dynamics and near-shore processes. Oceanography topics include: overview of atmospheric and thermal forcing of the oceans, ocean circulation, effects of topography and Earth's rotation, wind-driven currents in upper ocean, coastal upwelling, the Gulf Stream, tidal flows, wave propagation, tsunamis.

APMA 1940L. Mathematical Models in Biophysics.
Development mathematical descriptions of biological systems aid in understanding cell function and physiology. The course will explore a range of topics including: biomechanics of blood flow in arteries and capillaries, motile cells and chemotaxis, cell signaling and quorum sensing, and additional topics. Formulating and using numerical simulations will be a further component. Students will develop individual projects. Prerequisites: APMA 0360, or APMA 0340, or written permission.

APMA 1940M. The History of Mathematics.
The course will not be a systematic survey but will focus on specific topics in the history of mathematics such as Archimedes and integration. Oresme and graphing, Newton and infinitesimals, simple harmonic motion, the discovery of 'Fourier' series, the Monte Carlo method, reading and analyzing the original texts. A basic knowledge of calculus will be assumed.

APMA 1940N. Introduction to Mathematical Models in Computational Biology.
This course is designed to introduce students to the use of mathematical models in biology as well as some more recent topics in computational biology. Mathematical techniques will involve difference equations and dynamical systems theory, ordinary differential equations and some partial differential equations. These techinques will be applied in the study of many biological applications such as: (i) Difference Equations: population dynamics, red blood cell production, population genetics; (ii) Ordinary Differential Equations: predator/prey models, Lotka/Volterra model, modeling the evolution of the genome, heart beat model/cycle, tranmission dynamics of HIV and gonorrhea; (iii) Partial Differential Equations: tumor growth, modeling evolution of the genome, pattern formation. Prerequisites: APMA 0330 and 0340.

APMA 1940O. Approaches to Problem Solving in Applied Mathematics.
The aim of the course is to illustrate through the examination of unsolved (but elementary) problems the ways in which professional applied mathematicians approach the solution of such questions. Ideas considered include: choosing the "simplest" nontrivial example; generalization; and specification. Ways to think outside convention. Some knowledge of probability and linear algebra helpful.

Suggested reading.
"How to solve it", G. Polya
"Nonplussed", Julian Havil

APMA 1940P. Biodynamics of Block Flow and Cell Locomotion.

APMA 1940Q. Filtering Theory.
Filtering (estimation of a "state process" from noisy data) is an important area of modern statistics. It is of central importance in navigation, signal and image processing, control theory and other areas of engineering and science. Filtering is one of the exemplary areas where the application of modern mathematics and statistics leads to substantial advances in engineering. This course will provide a student with the working knowledge sufficient for cutting edge research in the field of nonlinear filtering and its practical applications. Topics will include: hidden Markov models, Kalman and Wiener filters, optimal nonlinear filtering, elements of Ito calculus and Wiener chaos, Zakai and Kushner equations, spectral separating filters and wavelet based filters, numerical implementation of filters. We will consider numerous applications of filtering to speech recognition, analysis of financial data, target tracking and image processing. No prior knowledge in the field is required but a good understanding of the basic Probability Theory (APMA1200 or APMA2630) is important.

APMA 1940R. Linear and Nonlinear Waves.
From sound and light waves to water waves and traffic jams, wave phenomena are everywhere around us. In this seminar, we will discuss linear and nonlinear waves as well as the propagation of wave packets. Among the tools we shall use and learn about are numerical simulations in Matlab and analytical techniques from ordinary and partial differential equations. We will also explore applications in nonlinear optics and to traffic flow problems. Prerequisites: MATH 0180 and either APMA 0330-0340 or APMA 0350-0360. No background in partial differential equations is required.

APMA 1940Y. Wavelets and Applications.
The aim of the course is to introduce you to: the relatively new and interdisciplinary area of wavelets; the efficient and elegants algorithms to which they give rise including the wavelet transform; and the mathematical tools that can be used to gain a rigorous understanding of wavelets. We will also cover some of the applications of these tools including the compression of video streams, approximation of solution of partial differential equations, and signal analysis.

APMA 1941D. Pattern Theory.
This course is an introduction to some probabilistic models and numerical algorithms that model some aspects of human cognition. The class begins with stochastic models of language introduced by Shannon and develops related models for speech and vision. The classes stresses mathematical foundations, in particular the role of information theory in developing Bayesian models and the increasing importance of dynamics in several algorithms, especially in optimization and deep learning. Student assessment will be based on computational projects that implement the principles discussed in lecture.

APMA 1970. Independent Study.
Section numbers vary by instructor. Please check Banner for the correct section number and CRN to use when registering for this course.

APMA 1971. Independent Study - WRIT.
Section numbers vary by instructor. Please check Banner for the correct section number and CRN to use when registering for this course. This course should be taken in place of APMA 1970 if it is to be used to satisfy the WRIT requirement.

APMA 2050. Mathematical Methods of Applied Science.
Introduces science and engineering graduate students to a variety of fundamental mathematical methods. Topics include linear algebra, complex variables, Fourier series, Fourier and Laplace transforms and their applications, ordinary differential equations, tensors, curvilinear coordinates, partial differential equations, and calculus of variations.

APMA 2060. Mathematical Methods of Applied Science.
Introduces science and engineering graduate students to a variety of fundamental mathematical methods. Topics include linear algebra, complex variables, Fourier series, Fourier and Laplace transforms and their applications, ordinary differential equations, tensors, curvilinear coordinates, partial differential equations, and calculus of variations.

APMA 2070. Deep Learning for Scientists & Engineers.
This course introduces concepts and implementation of deep learning techniques for computational science and engineering problems to first or second year graduate students. This course entails various methods, including theory and implementation of deep learning techniques to solve a broad range of problems using scientific machine learning. Lectures and tutorials on Python, Tensorflow and PyTorch are also included. Students will understand the underlying theory and mathematics of deep learning; analyze and synthesize data in order to model physical, chemical, biological, and engineering systems; and apply physics-informed neural networks and neural operators to model and simulate multiphysics systems. Undergraduate students who want to enroll in this course should request an override through Courses@Brown.

Spr	APMA2070	S01	26042	M	3:00-5:30(13)	(K. Shukla)

APMA 2080. Inference in Genomics and Molecular Biology.
Massive quantities of fundamental biological and geological sequence data have emerged. The goal of this course is to enable students to construct and apply probabilistic models to draw inferences from sequence data on problems novel to them. Statistical topics: Bayesian inferences; estimation; hypothesis testing and false discovery rates; statistical decision theory; change point algorithm; hidden Markov models; Kalman filters; and significances in high dimensions. Prerequisites: APMA 1650 or equivalent; APMA 0160 or CSCI 0111 or equivalent.

APMA 2110. Real Analysis.
Provides the basis of real analysis which is fundamental to many of the other courses in the program: metric spaces, measure theory, and the theory of integration and differentiation.

Fall	APMA2110	S01	17547	TTh	10:30-11:50(13)	(Y. Guo)

APMA 2110A. Real Function Theory (MATH 2210).
Interested students must register for MATH 2210.

APMA 2120. Hilbert Spaces and Their Applications.
A continuation of APMA 2110: metric spaces, Banach spaces, Hilbert spaces, the spectrum of bounded operators on Banach and Hilbert spaces, compact operators, applications to integral and differential equations.

Spr	APMA2120	S01	26043	TTh	1:00-2:20(08)	(Y. Guo)

APMA 2120A. Real Function Theory (MATH 2210).
Interested students must register for MATH 2220.

APMA 2130. Methods of Applied Mathematics: Partial Differential Equations.
Solution methods and basic theory for first and second order partial differential equations. Geometrical interpretation and solution of linear and nonlinear first order equations by characteristics; formation of caustics and propagation of discontinuities. Classification of second order equations and issues of well-posed problems. Green's functions and maximum principles for elliptic systems. Characteristic methods and discontinuous solutions for hyperbolic systems.

APMA 2140. Methods of Applied Mathematics: Integral Equations.
Integral equations. Fredholm and Volterra theory, expansions in orthogonal functions, theory of Hilbert-Schmidt. Singular integral equations, method of Wiener-Hopf. Calculus of variations and direct methods.

APMA 2160. Methods of Applied Mathematics: Asymptotics.
Calculus of asymptotic expansions, evaluation of integrals. Solution of linear ordinary differential equations in the complex plane, WKB method, special functions.

APMA 2170. Functional Analysis and Applications.
Topics vary according to interest of instructor and class.

APMA 2190. Nonlinear Dynamical Systems I.
Basic theory of ordinary differential equations, flows, and maps. Two-dimensional systems. Linear systems. Hamiltonian and integrable systems. Lyapunov functions and stability. Invariant manifolds, including stable, unstable, and center manifolds. Bifurcation theory and normal forms. Nonlinear oscillations and the method of averaging. Chaotic motion, including horseshoe maps and the Melnikov method. Applications in the physical and biological sciences.

Fall	APMA2190	S01	17548	TTh	2:30-3:50(12)	(B. Sandstede)

APMA 2200. Nonlinear Dynamical Systems: Theory and Applications.
Basic theory of ordinary differential equations, flows, and maps. Two-dimensional systems. Linear systems. Hamiltonian and integrable systems. Lyapunov functions and stability. Invariant manifolds, including stable, unstable, and center manifolds. Bifurcation theory and normal forms. Nonlinear oscillations and the method of averaging. Chaotic motion, including horseshoe maps and the Melnikov method. Applications in the physical and biological sciences.

Spr	APMA2200	S01	26044	TTh	2:30-3:50(11)	(G. Menon)

APMA 2210. Topics in Nonlinear Dynamical Systems.
Topics to be covered in this course may vary depending on the audiences. One of the goals that is planned for this course is to discuss the boundary layers and/or the boundary value problems that appear and play a very important role in the kinetic theory of gases; in particular, in the theory of the Boltzmann equations. Students are encouraged to attend and participate in the kinetic theory program offered by the ICERM institute in the Fall 2011 semester. This course may be taken twice for credit.

APMA 2230. Partial Differential Equations I.
The theory of the classical partial differential equations, as well as the method of characteristics and general first order theory. Basic analytic tools include the Fourier transform, the theory of distributions, Sobolev spaces, and techniques of harmonic and functional analysis. More general linear and nonlinear elliptic, hyperbolic, and parabolic equations and properties of their solutions, with examples drawn from physics, differential geometry, and the applied sciences. Generally, semester II of this course concentrates in depth on several special topics chosen by the instructor.

APMA 2240. Partial Differential Equations.
The theory of the classical partial differential equations, as well as the method of characteristics and general first order theory. Basic analytic tools include the Fourier transform, the theory of distributions, Sobolev spaces, and techniques of harmonic and functional analysis. More general linear and nonlinear elliptic, hyperbolic, and parabolic equations and properties of their solutions, with examples drawn from physics, differential geometry, and the applied sciences. Generally, semester II of this course concentrates in depth on several special topics chosen by the instructor.

APMA 2260. Introduction to Stochastic Control Theory.
The course serves as an introduction to the theory of stochastic control and dynamic programming technique. Optimal stopping, total expected (discounted) cost problems, and long-run average cost problems will be discussed in discrete time setting. The last part of the course deals with continuous time determinstic control and game problems. The course requires some familiarity with the probability theory.

APMA 2410. Fluid Dynamics I.
Formulation of the basic conservation laws for a viscous, heat conducting, compressible fluid. Molecular basis for thermodynamic and transport properties. Kinematics of vorticity and its transport and diffusion. Introduction to potential flow theory. Viscous flow theory; the application of dimensional analysis and scaling to obtain low and high Reynolds number limits.

APMA 2420. Fluid Mechanics II.
Introduction to concepts basic to current fluid mechanics research: hydrodynamic stability, the concept of average fluid mechanics, introduction to turbulence and to multiphase flow, wave motion, and topics in inviscid and compressible flow.

APMA 2450. Exchange Scholar Program.

Fall	APMA2450	S01	16534	Arranged		'To Be Arranged'
Spr	APMA2450	S01	25202	Arranged		'To Be Arranged'

APMA 2470. Topics in Fluid Dynamics.
Initial review of topics selected from flow stability, turbulence, turbulent mixing, surface tension effects, and thermal convection. Followed by focussed attention on the dynamics of dispersed two-phase flow and complex fluids.

APMA 2480. Topics in Fluid Dynamics.
No description available.

APMA 2550. Numerical Solution of Partial Differential Equations I.
Finite difference methods for solving time-dependent initial value problems of partial differential equations. Fundamental concepts of consistency, accuracy, stability and convergence of finite difference methods will be covered. Associated well-posedness theory for linear time-dependent PDEs will also be covered. Some knowledge of computer programming expected.

Fall	APMA2550	S01	17549	W	3:00-5:30(10)	(M. Ainsworth)

APMA 2560. Numerical Solution of Partial Differential Equations II.
An introduction to weighted residual methods, specifically spectral, finite element and spectral element methods. Topics include a review of variational calculus, the Rayleigh-Ritz method, approximation properties of spectral end finite element methods, and solution techniques. Homework will include both theoretical and computational problems.

Spr	APMA2560	S01	26045	W	3:00-5:30(10)	(B. Keith)

APMA 2570A. Numerical Solution of Partial Differential Equations III.
We will cover spectral methods for partial differential equations. Algorithm formulation, analysis, and efficient implementation issues will be addressed. Prerequisite: APMA 2550 or equivalent knowledge in numerical methods.

APMA 2570B. Numerical Solution of Partial Differential Equations III.
We will cover finite element methods for ordinary differential equations and for elliptic, parabolic and hyperbolic partial differential equations. Algorithm development, analysis, and computer implementation issues will be addressed. In particular, we will discuss in depth the discontinuous Galerkin finite element method. Prerequisite: APMA 2550 or equivalent knowledge in numerical methods.

Fall	APMA2570E	S01	19012	M	3:00-5:30(03)	(B. Keith)

APMA 2580A. Computational Fluid Dynamics.
The course will focus primarily on finite difference methods for viscous incompressible flows. Other topics will include multiscale methods, e.g. molecular dynamics, dissipative particle dynamics and lattice Boltzmann methods. We will start with the mathematical nature of the Navier-Stokes equations and their simplified models, learn about high-order explicit and implicit methods, time stepping, and fast solvers. We will then cover advection-diffusion equations and various forms of the Navier-Stokes equations in primitive variables and in vorticity/streamfunction formulations. In addition to the homeworks the students are required to develop a Navier-Stokes solver as a final project.

Spr	APMA2580A	S01	26046	TTh	10:30-11:50(09)	(J. Guzman)

APMA 2580B. Computational Fluid Dynamics for Compressible Flows.
An introduction to computational fluid dynamics with emphasis on compressible flows. We will cover finite difference, finite volume and finite element methods for compressible Euler and Navier-Stokes equations and for general hyperbolic conservation laws. Background material in hyperbolic partial differential equations will also be covered. Algorithm development, analysis, implementation and application issues will be addressed. Prerequisite: APMA 2550 or equivalent knowledge in numerical methods.

APMA 2580C. Optimization.
This course provides a solid presentation of modern convex analysis and convex optimization algorithms for large scale problems. Topics include: Ekeland's variational principle, subdifferential calculus, duality and Fenchel-Legendre transform, projection on a closed convex set, proximal operators and Moreau's regularization, accelerated and optimal first-order methods, Hopf/Lax-Oleinik representation formulas for Hamilton-Jacobi equations. The course will provide the mathematical and algorithmic underpinnings. It will also explore some applications in signal and image processing, optimal control and machine learning.

APMA 2610. Recent Applications of Probability and Statistics.
This course develops the mathematical foundations of modern applications of statistics to the computational, cognitive, engineering, and neural sciences. The course is rigorous, but the emphasis is on application. Topics include: Gibbs ensembles and their relation to maximum entropy, large deviations, exponential models and information theory; statistical estimation and classification; graphical models, dynamic programming, MCMC, parameter estimation, and the EM algorithm. Graduate version: 2610; Undergraduate version: 1740. Prerequisites: APMA 1650 or equivalent, programming experience, strong mathematics background. APMA 1200 or APMA 1690 or similar courses recommended. MATH 1010 or equivalent is recommended for APMA 2610.

Spr	APMA2610	S01	26041	MWF	2:00-2:50(07)	(O. Nguyen)

APMA 2630. Theory of Probability I.
Part one of a two semester course that provides an introduction to probability theory based on measure theory. The first semester (APMA 2630) covers the following topics: countable state Markov chains, review of real analysis and metric spaces, probability spaces, random variables and measurable functions, Borel-Cantelli lemmas, weak and strong laws of large numbers, conditional expectation and beginning of discrete time martingale theory. Prerequisites—undergraduate probability and analysis, co-requisite—graduate real analysis.

Fall	APMA2630	S01	17551	TTh	1:00-2:20(06)	(Y. Shenfeld)

APMA 2640. Theory of Probability II.
Part two of a two semester course that provides an introduction to probability theory based on measure theory. Standard topics covered in the second-semester (APMA 2640) include the following: discrete time martingale theory, weak convergence (also called convergence in distribution) and the central limit theorem, and a study of Brownian motion. Optional topics include the ergodic theorem and large deviation theory. Prerequisites—undergraduate probability and analysis, co-requisite—graduate real analysis.

Spr	APMA2640	S01	26047	TTh	9:00-10:20(05)	'To Be Arranged'

APMA 2660. Stochastic Processes.
Review of the theory of stochastic differential equations and reflected SDEs, and of the ergodic and stability theory of these processes. Introduction to the theory of weak convergence of probability measures and processes. Concentrates on applications to the probabilistic modeling, control, and approximation of modern communications and queuing networks; emphasizes the basic methods, which are fundamental tools throughout applications of probability.

APMA 2670. Mathematical Statistics I.
This course presents advanced statistical inference methods. Topics include: foundations of statistical inference and comparison of classical, Bayesian, and minimax approaches, point and set estimation, hypothesis testing, linear regression, linear classification and principal component analysis, MRF, consistency and asymptotic normality of Maximum Likelihood and estimators, statistical inference from noisy or degraded data, and computational methods (E-M Algorithm, Markov Chain Monte Carlo, Bootstrap). Prerequisite: APMA 2630 or equivalent.

Fall	APMA2670	S01	17552	Th	4:00-6:30(04)	(B. Gidas)

APMA 2680. Mathematical Statistics II.
The course covers modern nonparametric statistical methods. Topics include: density estimation, multiple regression, adaptive smoothing, cross-validation, bootstrap, classification and regression trees, nonlinear discriminant analysis, projection pursuit, the ACE algorithm for time series prediction, support vector machines, and neural networks. The course will provide the mathematical underpinnings, but it will also touch upon some applications in computer vision/speech recognition, and biological, neural, and cognitive sciences. Prerequisite: APMA 2670.

Spr	APMA2680	S01	26048	Th	4:00-6:30(17)	(B. Gidas)

APMA 2720. Information Theory.
Information theory and its relationship with probability, statistics, and data compression. Entropy. The Shannon-McMillan-Breiman theorem. Shannon's source coding theorems. Statistical inference; hypothesis testing; model selection; the minimum description length principle. Information-theoretic proofs of limit theorems in probability: Law of large numbers, central limit theorem, large deviations, Markov chain convergence, Poisson approximation, Hewitt-Savage 0-1 law. Prerequisites: APMA 2630, 1710.

APMA 2810A. Computational Biology.
Provides an up-to-date presentation of the main problems and algorithms in bioinformatics. Emphasis is given to statistical/ probabilistic methods for various molecular biology tasks, including: comparison of genomes of different species, finding genes and motifs, understanding transcription control mechanisms, analyzing microarray data for gene clustering, and predicting RNA structure.

APMA 2810B. Computational Molecular Biology.
Provides an up-to-date presentation of problems and algorithms in bioinformatics, beginning with an introduction to biochemistry and molecular genetics. Topics include: proteins and nucleic acids, the genetic code, the central dogma, the genome, gene expression, metabolic transformations, and experimental methods (gel electrophoresis, X-ray crystallography, NMR). Also, algorithms for DNA sequence alignment, database search tools (BLAST), and DNA sequencing.

APMA 2810C. Elements of High Performance Scientific Computing.
No description available.

APMA 2810D. Elements of High Performance Scientific Computing II.
No description available.

APMA 2810E. Far Field Boundary Conditions for Hyperbolic Equations.
No description available.

APMA 2810F. Introduction to Non-linear Optics.
No description available.

APMA 2810G. Large Deviations.
No description available.

APMA 2810H. Math of Finance.
No description available.

APMA 2810I. Mathematical Models and Numerical Analysis in Computational Quantum Chemistry.
We shall present on some models in the quantum chemistry field (Thomas Fermi and related, Hartree Fock, Kohn Sham) the basic tools of functional analysis for the study of their solutions. Then some of the discretization methods and iterative algorithms to solve these problems will be presented and analyzed. Some of the open problems that flourish in this field will also be presented all along the lectures.

APMA 2810J. Mathematical Techniques for Neural Modeling.
No description available.

APMA 2810K. Methods of Algebraic Geometry in Control Theory I.
Develops the ideas of algebraic geometry in the context of control theory. The first semester examines scalar linear systems and affine algebraic geometry while the second semester addresses multivariable linear systems and projective algebraic geometry.

APMA 2810L. Numerical Solution of Hyperbolic PDE's.
No description available.

APMA 2810M. Some Topics in Kinetic Theory.
Nonlinear instabilities as well as boundary effects in a collisionless plasmas; Stable galaxy configurations; A nonlinear energy method in the Boltzmann theory will also be introduced. Self-contained solutions to specific concrete problems. Focus on ideas but not on technical aspects. Open problems and possible future research directions will then be discussed so that students can gain a broader perspective. Prerequisite: One semester of PDE (graduate level) is required.

APMA 2810N. Topics in Nonlinear PDEs.
Aspects of the theory on nonlinear evolution equations, which includes kinetic theory, nonlinear wave equations, variational problems, and dynamical stability.

APMA 2810O. Stochastic Differential Equations.
This course develops the theory and some applications of stochastic differential equations. Topics include: stochastic integral with respect to Brownian motion, existence and uniqueness for solutions of SDEs, Markov property of solutions, sample path properties, Girsanov's Theorem, weak existence and uniqueness, and connections with partial differential equations. Possible additional topics include stochastic stability, reflected diffusions, numerical approximation, and stochastic control. Prerequisite: APMA 2630 and 2640.

APMA 2810P. Perturbation Methods.
Basic concepts of asymptotic approximations with examples with examples such as evaluation of integrals and functions. Regular and singular perturbation problems for differential equations arising in fluid mechanics, wave propagation or nonlinear oscillators. Methods include matched asymptotic expansions and multiple scales. Methods and results will be discussed in the context of applications to physical problems.

APMA 2810Q. Discontinous Galerkin Methods.
In this seminar course we will cover the algorithm formulation, stability analysis and error estimates, and implementation and applications of discontinuous Galerkin finite element methods for solving hyperbolic conservation laws, convection diffusion equations, dispersive wave equations, and other linear and nonlinear partial differential equations. Prerequisite: APMA 2550.

Fall	APMA2810Q	S01	17553	M	3:00-5:30(03)	(C. Shu)

APMA 2810R. Computational Biology Methods for Gene/Protein Networks and Structural Proteomics.
The course presents computational and statistical methods for gene and protein networks and structural proteomics; it emphasizes: (1) Probablistic models for gene regulatory networks via microarray, chromatin immunoprecipitation, and cis-regulatory data; (2) Signal transduction pathways via tandem mass spectrometry data; (3) Molecular Modeling forligand-receptor coupling and docking. The course is recommended for graduate students.

APMA 2810S. Topics in Control.
No description available.

APMA 2810T. Nonlinear Partial Differential Equations.
This course introduces techniques useful for solving many nonlinear partial differential equations, with emphasis on elliptic problems. PDE from a variety of applications will be discussed. Contact the instructor about prerequisites.

APMA 2810U. Topics in Differnetial Equations.
No description available.

APMA 2810V. Topics in Partial Differential Equations.
The course will cover an introduction of the L_p theory of second order elliptic and parabolic equations, finite difference approximations of elliptic and parabolic equations, and some recent developments in the Navier-Stokes equations and quasi-geostrophic equations. Some knowledge of real analysis will be expected.

APMA 2810W. Advanced Topics in High Order Numerical Methods for Convection Dominated Problems.
This is an advanced seminar course. We will cover several topics in high order numercial methods for convection dominated problems, including methods for solving Boltzman type equations, methods for solving unsteady and steady Hamilton-Jacobi equations, and methods for solving moment models in semi-conductor device simulations. Prerequisite: APMA 2550 or equivalent knowledge of numerical analysis.

APMA 2810X. Introduction to the Theory of Large Deviations.
The theory of large deviations attempts to estimate the probability of rare events and identify the most likely way they happen. The course will begin with a review of the general framework, standard techniques (change-of-measure, PDE, weak convergence, etc.), and basic examples (e.g., Sanov's and Cramer's Theorems). We then will cover the Wentsel-Freidlin theory. The last part of the course will be one or two related topics, possibly drawn from (but not limited to) risk-sensitive control and Monte Carlo methods. Prerequisites: APMA 2630 and 2640.

APMA 2810Y. Discrete high-D Inferences in Genomics.
Genomics is revolutionizing biology and biomedicine and generated a mass of clearly relevant high-D data along with many important high-D discreet inference problems. Topics: special characteristics of discrete high-D inference including Bayesian posterior inference; point estimation; interval estimation; hypothesis tests; model selection; and statistical decision theory.

APMA 2810Z. An Introduction to the Theory of Large Deviations.
The theory of large deviations attempts to estimate the probability of rare events and identify the most likely way they happen. The course will begin with a review of the general framework, standard techniques (change-of-measure, subadditivity, etc.), and elementary examples (e.g., Sanov's and Cramer's Theorems). We then will cover large deviations for diffusion processes and the Wentsel-Freidlin theory. The last part of the course will be one or two related topics, possibly drawn from (but not limited to) risk-sensitive control; weak convergence methods; Hamilton-Jacobi-Bellman equations; Monte Carlo methods. Prerequisites: APMA 2630 and 2640.

APMA 2811A. Directed Methods in Control and System Theory.
Various general techniques have been developed for control and system problems. Many of the methods are indirect. For example, control problems are reduced to a problem involving a differential equation (such as the partial differential equation of Dynamic Programming) or to a system of differential equations (such as the canonical system of the Maximum Principle). Since these indirect methods are not always effective alternative approaches are necessary. In particular, direct methods are of interest.

We deal with two general classes, namely: 1.) Integration Methods; and, 2.) Representation Methods. Integration methods deal with the integration of function space differential equations. Perhaps the most familiar is the so-called Gradient Method or curve of steepest descent approach. Representation methods utilize approximation in function spaces and include both deterministic and stochastic finite element methods. Our concentration will be on the theoretical development and less on specific numerical procedures. The material on representation methods for Levy processes is new.

APMA 2811B. Computational Methods for Signaling Pathways and Protein Interactions.
The course will provide presentation of the biology and mathematical models/algorithms for a variety of topics, including: (1) The analysis and interpretation of tandem mass spectrometry data for protein identification and determination of signaling pathways, (2) Identification of Phosphorylation sites and motifs and structural aspects of protein docking problems. Prerequisites: The course is recommended for graduate students. It will be self-contained; students will be able to fill in knowledge by reading material to be indicated by the instructor.

APMA 2811C. Stochastic Partial Differential Equations.
SPDEs is an interdisciplinary area at the crossroads of stochastic processes and partial differential equations (PDEs). The topics of the course include: geneses of SPDEs in real life applications, mathematical foundations and analysis of SPDEs, numerical and computational aspects of SPDEs, applications of SPDEs to fluid dynamics, population biology, hidden Markov models, etc. Prerequisites: familiarity with stochastic calculus and PDEs (graduate level).

APMA 2811D. Asymptotic Problems For Differential Equations And Stochastic Processes.
Topics that will be covered include: WKB method: zeroth and first orders; turning points; Perturbation theory: regular perturbation, singular perturbation and boundary layers; Homogenization methods for ODE's, elliptic and parabolic PDE's; Homogenization for SDE's, diffusion processes in periodic and random media; Averaging principle for ODE's and SDE's. Applications will be discussed in class and in homework problems.

APMA 2811E. A Posteriori Estimates for Finite Element Methods.
This course gives an introduction to the the basic concepts of a posteriori estimates of finite element methods. After an overview of different techniques the main focus will be shed on residual based estimates where as a starting point the Laplace operator is analyzed. Effectivity and reliability of the error estimator will be proven. In a second part of the course, students will either study research articles and present them or implement the error estimates for some specific problem and present their numerical results. Recommended prerequisites: basic knowledge in finite elements, APMA 2550, 2560, 2570.

APMA 2811F. Numerical Solution of Ordinary Differential Equations: IVP Problems and PDE Related Issues.
The purpose of the course is to lay the foundation for the development and analysis of numerical methods for solving systems of ordinary differential equations. With a dual emphasis on analysis and efficient implementations, we shall develop the theory for multistage methods (Runge-Kutta type) and multi-step methods (Adams/BDF methods). We shall also discuss efficient implementation strategies using Newton-type methods and hybrid techniques such as Rosenbruck methods. The discussion includes definitions of different notions of stability, stiffness and stability regions, global/local error estimation, and error control. Time permitting, we shall also discuss more specialized topics such as symplectic integration methods and parallel-in-time methods. A key component of the course shall be the discussion of problems and methods designed with the discretization of ODE systems originating from PDE's in mind. Topics include splitting methods, methods for differential-algebraic equations (DAE),deferred correction methods. and order reduction problems for IBVP, TVD and IMEX methods. Part of the class will consist of student presentations on more advanced topics, summarizing properties and known results based on reading journal papers.

APMA 2811G. Topics in Averaging and Metastability with Applications.
Topics that will be covered include: the averaging principle for stochastic dynamical systems and in particular for Hamiltonian systems; metastability and stochastic resonance. We will also discuss applications in class and in homework problems. In particular we will consider metastability issues arising in chemistry and biology, e.g. in the dynamical behavior of proteins. The course will be largely self contained, but a course in graduate probability theory and/or stochastic calculus will definitely help.

APMA 2811I. An Introduction to Turbulence Modeling.
Turbulence is the last mystery of classical physics. It surrounds us everywhere – in the air, in the ocean, in pipes carrying fluids and even in human body arteries. The course helps to understand what makes modeling the turbulence so difficult and challenging. The course covers the following issues: The nature of turbulence, characteristics of turbulence and classical constants of turbulence; Turbulent scales; Navier-Stokes equations, Reynolds stresses and Reynolds-Averaged Navier-Stokes (RANS) equations; RANS turbulence models: algebraic models, one-equation models, two-equation models; Low-Reynolds number turbulence models; Renormalization Group (RNG) turbulence model; Large-Eddy Simulation (LES); Students will be provided with user-friendly computer codes to run different benchmark cases. The final grade is based on two take home projects - computing or published papers analysis, optionally.

APMA 2811K. Computational/Statistical Methods for Signaling Pathways and Protein Interactions.
The course will cover the main mathematical/computational models/algorithms for a variety of tasks in proteomics and structural proteomics, including: (1) The analysis and interpretation of tandem mass spectrometry data for protein identification and determination of signaling pathways, (2) Identification of Phosphorylation sites and motifs, and (3) structural aspects of protein docking problems on the basis of NMR data. Open to graduate students only.

APMA 2811L. Topics in Homogenization: Theory and Computation.
Topics that will be covered include: Homogenization methods for ODE's, for elliptic and parabolic PDE's and for stochastic differential Equations (SDE's) in both periodic and random media; Averaging principle for ODE's and SDE's. Both theoretical and computational aspects will be studied. Applications will be discussed in class and in homework problems. Prerequisites: Some background in PDE's and probability will be helpful, even though the class will be largely self contained.

APMA 2811O. Dynamics and Stochastics.
This course provides a synthesis of mathematical problems at the interface between stochastic problems and dynamical systems that arise in systems biology. For instance, in some biological systems some species may be modeled stochastically while other species can be modeled using deterministic dynamics. Topics will include an introduction to biological networks, multiscale analysis, analysis of network structure, among other topics. Prerequisites: probability theory (APMA 2630/2640, concurrent enrollment in APMA 2640 is acceptable).

APMA 2811Q. Calculus of Variations.
An introduction to modern techniques in the calculus of variations. Topics covered will include: existence of solutions and the direct method, Euler-Lagrange equations and necessary and sufficient conditions, one-dimensional problems, multidimensional nonconvex problems, relaxation and quasiconvexity, Young's measures, and singular perturbations. The emphasis of the course will be equal parts theory and applications with numerous examples drawn from topics in nonlinear elasticity, pattern formation, wrinkling thin elastic sheets, martensitic phase transitions, minimal surfaces, differential geometry and optimal control.

APMA 2811S. Levy Processes.
Lévy processes are the continuous-time analogues of random walks, and include Brownian motion, compound Poisson processes, and square-integrable pure-jump martingales with many small jumps. In this course we will develop the basic theory of general Lévy processes and subordinators, and discuss topics including local time, excursions, and fluctuations. Time permitting we will finish with selected applications which are of mutual interest to the instructor and students enrolled in the class. Prerequisite: APMA 2640 or equivalent.

APMA 2811X. Finite Element Exterior Calculus.
In this course we will cover finite elements for the Hodge Laplacian. We start in three dimensions and discuss the Nedelec finite element spaces for H^1, H(curl) and H(div) and discuss the corresponding de Rham complex. We discuss how they can be applied to the Stokes problem and electro-magnetic problems. We then generalize these spaces to higher dimensions and show how to use them to approximate the Hodge Laplacian. We will mostly follow the review paper: [Finite Element Exterior Calculus: from Hodge Theory to Numerical Stability].

APMA 2811Z. Stochastic Partial Differential Equations: Theory and Numerics.
This course introduces basic theory and numerics of stochastic partial differential equations (SPDEs). Topics include Brownian motion and stochastic calculus in Hilbert spaces, classification of SPDEs and solutions, stochastic elliptic, hyperbolic and parabolic equations, regularity of solutions, linear and nonlinear equations, analytic and numerical methods for SPDEs. Topics of particular interest will also be discussed upon agreements between the instructor and audience.
All three courses APMA 2630, APMA 2640, APMA 2550 are background recommended but not required.

APMA 2812A. An Introduction to Stochastic Control.
This is a course on the optimal control of random processes. The first part of the course will focus on discrete time and the optimal control of Markov chains (also called Markov Decision Theory in the context of Reinforcement Learning). Various optimality criteria are introduced and questions of existence of solutions to the corresponding Bellman equation and characterization of optimal controls are addressed. Applications from finance, engineering and optimal stopping will be developed, as well as methods for numerical solution of the Bellman equation. We then consider problems in continuous time, and the difficulties that occur when there is no classical sense solution to the corresponding Bellman equation. If time permits, other applications areas and models with partial observations may be considered. Prerequisites: APMA 2630/2640.

APMA 2812B. An Introduction to SPDE's.
An introduction to the basic theory of Stochastic PDE's. Topics will likely include (time permitting) Gaussian measure theory, stochastic integration, stochastic convolutions, stochastic evolution equations in Hilbert spaces, Ito's formula, local well-posedness for semi-linear SPDE with additive noise, weak Martingale solutions to 3D Navier-Stokes, Markov processes on Polish spaces, the Krylov–Bogolyubov theorem, the Doob-Khasminskii theorem, and Bismut-Elworthy-Li formula for a class of non-degenerate SPDE. The presentation will be largely self contained, but will assume some basic knowledge in measure theory, functional analysis, and probability theory. Some familiarity with SDE and PDE is also very helpful, but not required.

APMA 2812E. Semidefinite and Combinatorial Optimization..
The course provides an introduction to basic mathematical theory and computational methods for semidefinite optimization with a particular focus on polynomial optimization problems. Topics include: duality, semialgebraic sets, polynomial optimization, sum of squares, spectrahedron, semidefinite relaxation, combinatorial optimization. Prerequisites: Math 0520, 0540, or equivalent, basic programming skills. Math 1530 is recommended.

APMA 2820A. A Tutorial on Particle Methods.
No description available.

APMA 2820B. Advanced Topics in Information Theory.
Explores classical and recent results in information theory. Topics chosen from: multi-terminal/network information theory; communication under channel uncertainty; side information problems (channel, source, and the duality between them); identification via channels; and multi-antenna fading channels. Prerequisite: APMA 1710 or basic knowledge of information theory.

APMA 2820C. Computational Electromagnetics.
No description available.

APMA 2820D. Conventional, Real and Quantum Computing with Applications to Factoring and Root Finding.
No description available.

APMA 2820E. Geophysical Fluid Dynamics.
No description available.

APMA 2820F. Information Theory and Networks.
No description available.

APMA 2820G. Information Theory, Statistics and Probability.
No description available.

APMA 2820H. Kinetic Theory.
We will focus on two main topics in mathematical study of the kinetic theory: (1) The new goal method to study the trend to Maxwellians; (2) various hydrodynamical (fluids) limits to Euler and Navier-Stokes equations. Main emphasis will be on the ideas behind proofs, but not on technical details.

APMA 2820I. Multiscale Methods and Computer Vision.
Course will address some basic multiscale computational methods such as: multigrid solvers for physical systems, including both geometric and algebraic multigrid, fast integral transforms of various kinds (including a fast Radon transform), and fast inverse integral transforms. Basic problems in computer vision such as global contour detection and their completion over gaps, image segmentation for textural images and perceptual grouping tasks in general will be explained in more details.

APMA 2820J. Numerical Linear Algebra.
Solving large systems of linear equations: The course will use the text of Treften and BAO that includes all the modern concepts of solving linear equations.

APMA 2820K. Numerical Solution of Ordinary Differential Equations.
We discuss the construction and general theory of multistep and multistage methods for numerically solving systems of ODE's, including stiff and nonlinear problems. Different notions to stability and error estimation and control. As time permits we shall discuss more advanced topics such as order reduction, general linear and additive methods, symplectic methods, and methods for DAE. Prerequisites: APMA 2190 and APMA 2550 or equivalent. Some programming experience is expected.

APMA 2820L. Random Processes in Mechanics.
No description available.

APMA 2820M. Singularities in Eliptic Problems and their Treatment by High-Order Finite Element Methods.
Singular solutions for elliptic problems (elasticity and heat transfer) are discussed. These may arise around corners in 2-D and along edges and vertices in 3-D domains. Derivation of singular solutions, charactized by eigenpairs and generalized stress/flux intensity factors (GSIF/GFIFs) are a major engineering importance (because of failure initiation and propagation). High-order FE methods are introduced, and special algorithms for extracting eigenpairs and GSIF/GFIFs are studied (Steklov, dual-function, ERR method, and others).

APMA 2820N. Topics in Scientific Computing.
No description available.

APMA 2820O. The Mathematics of Shape with Applications to Computer Vision.
Methods of representing shape, the geometry of the space of shapes, warping and matching of shapes, and some applications to problems in computer vision and medical imaging. Prerequsite: See instructor for prerequisites.

APMA 2820P. Foundations in Statistical Inference in Molecular Biology.
In molecular biology, inferences in high dimensions with missing data are common. A conceptual framework for Bayesian and frequentist inferrnces in this setting including: sequence alignment, RNA secondary structure prediction, database search, and functional genomics. Statistical topics: parameter estimation, hypothesis testing, and characterization of posterior spaces. Core course in proposed PhD program in computational molecular biology.

APMA 2820Q. Topics in Kinetic Theory.
This course will introduce current mathematical study for Boltzmann equation and Vlasov equation. We will study large time behavior and hydrodynamic limits for Boltzmann theory and instabilities in the Vlasov theory. Graduate PDE course is required.

APMA 2820R. Structure Theory of Control Systems.
The course deals with the following problems: given a family of control systems S and a family of control systems S', when does there exist an appropriate embedding of S into S' ? Most of the course will deal with the families of linear control systems. Knowledge of control theory and mathematical sophistication are required.

APMA 2820S. Topics in Differential Equations.
A sequel to APMA 2210 concentrating on similar material.

APMA 2820T. Foundations in Statistical Inference in Molecular Biology.
In molecular biology, inferences in high dimensions with missing data are common. A conceptual framework for Bayesian and frequentist inferences in this setting including: sequence alignment. RNA secondary structure prediction, database search, and tiled arrays. Statistical topics: parameter estimation, hypothesis testing, recursions, and characterization of posterior spaces. Core course in proposed PhD program in computational molecular biology.

APMA 2820U. Structure Theory of Control Systems.
The course deals with the following problems: given a family of control systems S and a family of control systems S', when does there exist an appropriate embedding of S into S' ? Most of the course will deal with the families of linear control systems. Knowledge of control theory and mathematical sophistication are required.

APMA 2820V. Progress in the Theory of Shock Waves.
Course begins with self-contained introduction to theory of "hyperbolic conservation laws", that is quasilinear first order systems of partial differential equations whose solutions spontaneously develop singularities that propagate as shock waves. A number of recent developments will be discussed. Aim is to familiarize the students with current status of the theory as well as with the expanding areas of applications of the subject.

APMA 2820W. An Introduction to the Theory of Large Deviations.
The theory of large deviations attempts to estimate the probability of rare events and identify the most likely way they happen. The course will begin with a review of the general framework, standard techniques (change-of-measure, subadditivity, etc.), and elementary examples (e.g., Sanov's and Cramer's Theorems). We then will cover large deviations for diffusion processes and the Wentsel¿Freidlin theory. The last part of the course will be one or two related topics, possibly drawn from (but not limited to) risk¿sensitive control; weak convergence methods; Hamilton-Jacobi-Bellman equations; Monte Carlo methods. Prerequisites: APMA 2630 and 2640.

APMA 2820X. Boundary Conditions for Hyperbolic Systems: Numerical and Far Field.

APMA 2820Y. Approaches to Problem Solving in Applied Mathematics.
TBA

APMA 2820Z. Topics in Discontinuous Galerkin Methods.
We will cover discontinuous Galerkin methods for time-dependent and steady state problems. Stability and error estimates of different discontinuous Galerkin methods will be discussed. In particular, we will discuss in depth the local discontinuous Galerkin method. Prerequisite: APMA 2550 or equivalent knowledge of numerical analysis.

APMA 2821A. Parallel Scientific Computing: Algorithms and Tools.
No description available.

APMA 2821B. To Be Determined.

APMA 2821C. Topics in Partial Differential Equations.
The course will start by reviewing the theory of elliptic and parabolic equations in Holder spaces. Then we will discuss several topics in nonlinear elliptic and parabolic equations, for instance, the Navier-Stokes equation and Monge-Ampere type equations. This course is a sequel to APMA 2810V, but APMA 2810V is not a prerequisite.

APMA 2821D. Random Processes and Random Variables.

APMA 2821E. Topics in Variational Methods.
This course consists of two parts: a general introduction to variational methods in PDE, and a more focused foray into some special topics. For the former we will cover the direct method in the calculus of variations, various notions of convexity, Noether's theorem, minimax methods, index theory, and gamma-convergence. For the latter we will focus on several specific problems of recent interest, with emphasis on the Ginzburg-Landau energy functional.

APMA 2821F. Computational Linear Algebra.
The course will cover basic and advanced algorithms for solution of linear and nonlinear systems as well as eigenvalue problems.

APMA 2821H. Introduction to High Performance Computing: Tools and Algorithms.
This course will cover fundamental concepts of parallel computing: shared and distributed memory models; metrics for performance measuring; roof-line model for analysis of computational kernels, prediction and improving their performance on different processors; code optimization. We will analyze algorithms maximizing data reuse, and memory bandwidth utilization. Prior experience in coding is a plus. One course meeting will take place at IBM/Research, students will interact with experts in areas of HPC, visualization, social media and more. There will be bi-weekly homework assignments and a final project. Students are encouraged to suggest final project relevant to their research and level of expertise.

APMA 2821I. Formulation and Approximation of Linear and Non-linear Problems of Solid Mechanics.
Presents the formulation and approximation by the Finite Element Method (FEM) of linear and non-linear problems of Solid Mechanics. The formulation of problems is based on the Virtual Work Principle (VWP). Increasing complexity problems will be considered such as simple bar under traction, beams, plates, plane problems and solids with linear and hyperelastic materials. All problems are formulated using the same sequence of presentation which includes kinematics, strain measure, rigid body deformation, internal work, external work, VWP and constitutive equations. The approximation of the given problems is based on the High-order FEM. Examples will be presented using a Matlab code.

APMA 2821J. Some Topics in Kinetic Theory.
In this advanced topic course, we will go over several aspects of recent mathematical work on kinetic theory. Graduate level PDE is required.

APMA 2821K. Probabilistic and Statistical Models for Graphs and Networks.
Many modern data sets involve observations about a network of interacting components. Probabilistic and statistical models for graphs and networks play a central role in understanding these data sets. This is an area of active research across many disciplines. Students will read and discuss primary research papers and complete a final project.

APMA 2821L. Introduction to Malliavin Calculus.
The Malliavin calculus is a stochastic calculus for random variables on Gaussian probability spaces, in particular the classical Wiener space. It was originally introduced in the 1970s by the French mathematician Paul Malliavin as a probabilistic approach to the regularity theory of second-order deterministic partial differential equations. Since its introduction, Malliavin's calculus has been extended beyond its original scope and has found applications in many branches of stochastic analysis; e.g. filtering and optimal control, mathematical finance, numerical methods for stochastic differential equations. This course will introduce, starting in a simple setting, the basic concepts and operations of the Malliavin calculus, which will then be applied to the study of regularity of stochastic differential equations and their associated partial differential equations. In addition, applications from optimal control and finance, including the Clark-Ocone foruma and its connection with hedging, will be presented.

APMA 2821M. Some Mathematical Problems in Materials Science.
We will study a variety of mathematical models for problems in materials science. Mainly we will consider models of phase transformation, static and dynamic. Some of the topics to be treated are: (1) models of phase transformation; (2) gradient flows; (3) kinetic theories of domain growth; (4) stochastic models; (5) free boundary problems. A working familiarity with partial differential equations is required.

APMA 2821N. Numerical Solution of Ordinary Differential Equations: IVP Problems and PDE Related Issues.
The course seeks to lay the foundation for the development and analysis of numerical methods for solving systems of ordinary differential equations. With a dual emphasis on analysis and efficient implementations, we shall develop the theory for multistage methods (Runge-Kutta type) and multi-step methods (Adams/BDF methods). The discussion includes definitions of different notions of stability, stiffness and stability regions, global/local error estimation, and error control. We also discuss more specialized topics such as symplectic integration methods, parallel-in-time methods, include splitting methods, methods for differential-algebraic equations (DAE), deferred correction methods, and order reduction problems for IBVP, TVD and IMEX methods.

APMA 2821O. Topics in Posteriori Error Estimations: Finite Element and Reduced Basis Methods.
The course will contain two related parts. An introduction of different types of a posteriori error estimations for various finite element methods, certified reduced basis method, where a posteriori error estimations play an important role. Emphasize both the theory and implementation. Related Matlab programs. Residual-type, local-problem type, and recovery-type error estimators for conforming, mixed, non-conforming, and discontinuous galerkin finite element methods for different types of equations. Reduced basis methods, offline-online procedure, greedy algorithm, error estimator, empirical interpolation method, and successive constraint method will be discussed. Goal-Oriented primal-dual approach for both FEM and RBM will be covered. Objective: To learn various theoretical and practical results of adaptive finite element methods and reduced basis methods.

APMA 2821P. Topics in the Atomistic-to-Continuum Coupling Methods for Material Science.
Atomistic-to-continuum coupling methods (a/c methods) have been proposed to increase the computational efficiency of atomistic computations involving the interaction between local crystal defects with long-range elastic fields. This course provides an introduction to the fundamentals required to understand modeling and computer simulation of material behavior. This course will first briefly review material from continuum mechanics, materials science including crystals and defects and then move on to advanced topics in development and analysis of a/c coupling methods both in static and dynamic cases. I will also select topics from statistical mechanics and temporal multiscale accelerated molecular dynamics methods (hyperdynamics, parallel replica dynamics).

APMA 2821R. Topics in the Atomistic-to-Continuum Coupling Methods for Material Science.
Atomistic-to-continuum coupling methods (a/c methods) have been proposed to increase the computational efficiency of atomistic computations involving the interaction between local crystal defects with long-range elastic fields.

This is an advanced topics course for graduate students. Provides an introduction to the fundamentals required to understand modeling and computer simulation of material behavior. First briefly review material from continuum mechanics, materials science including crystals and defects and then move on to advanced topics in development and analysis of a/c coupling methods both in static and dynamic cases. select topics from statistical mechanics and temporal multiscale accelerated molecular dynamics methods (hyperdynamics, parallel replica dynamics).

APMA 2821T. Theory of Large Deviations.
The theory of large deviations is concerned with the probabilities of very rare events. There are many applications where a rare event can have a significant impact (think of the lottery) and it is of interest to know when and how these events occur. The course will begin with a review of the general framework, standard techniques, and elementary examples (e.g., Cramer's and Sanov's Theorems) before proceeding with general theory and applications. If time permits, the course will end with a study of large deviations for diffusion processes.

APMA 2821U. Kinetic Theory.
Topics in kinetic theory, particularly concerning Boltzmann equations and related but simpler models (e.g.the Kac model). Key issues include the mathematical derivation of the Boltzmann equation, the Cauchy problem, Boltzmann's H theorem, and hydrodynamic limits yielding the equations of fluid mechanics. We will be most interested in rigorous results, but will not turn away from formal calculations when these are the only things available. A probabilistic viewpoint will be emphasized. In addition to these "traditional" topics, we will also introduce the Smoluchowski coagulation equation and a similar equation, and some microscopic models described by these in the kinetic limit or exactly. Students should have PDE background equivalent to or exceeding MATH 2370/APMA 2230. Familiarity with probability will be helpful, but we will review this according to the audience's needs.

APMA 2821V. Neural Dynamics: Theory and Modeling.
Our thoughts and actions are mediated by the dynamic activity of the brain’s neurons. This course will use mathematics and computational modeling as a tool to study neural dynamics at the level of signal neurons and in more complicated networks. We will focus on relevance to modern day neuroscience problems with a goal of linking dynamics to function. Topics will include biophysically detailed and reduced representations of neurons, bifurcation and phase plane analysis of neural activity, neural rhythms and coupled oscillator theory. Audience: advanced undergraduate or graduate students. Prerequisite: APMA 0350-0360 and Matlab programming course. Instructor permission required.

APMA 2822B. Introduction to Parallel Computing on Heterogeneous (CPU+GPU) Systems.
This course we will learn fundamental aspects of parallel computing on heterogeneous systems composed of multi-core CPUs and GPUs. This course will contain lectures and hands-on parts. We will cover the following topics: shared memory and distributed memory programming models, parallelization strategies and nested parallelism. We will also learn techniques for managing memory and data on systems with heterogeneous memories (DDR for CPUs and HBM for GPUs); parallelization strategies using OpenMP and MPI; programming GPUs using OpenMP4.5 directives and CUDA. We will focus on programming strategies and application performance. Grading will be based on homework assignments, and final project.

Fall	APMA2822E	S01	17554	F	3:00-5:30(11)	'To Be Arranged'

APMA 2822G. Topics in Optimal Transport and High Dimensional Probability.
The study of probability distributions in high dimensions is prevalent in current research in theoretical and applied mathematics, as well as in science and engineering. This course will cover the foundations of some of the tools used in the field: optimal transport, probability flows, concentration of measure, as well as other fundamental topics.

Spr	APMA2822G	S01	26205	M	3:00-5:30(13)	(Y. Shenfeld)

APMA 2822H. Topics in Approximation Theory.
Approximation theory lies at the heart of almost every computational method. Although approximation theory is a vast subject that has been studied for centuries it is still an area of current active research, and encompasses many methods including polynomial, neural networks, Fourier series, splines, wavelets, radial basis functions to name but a few. This class aims to cover a wide range of topics in approximation theory that are relevant for those interested in numerical approximation of functions, data and differential equations. We shall cover fundamental theory of polynomial approximation before moving on to topics including multiresolution analysis, wavelets and neural networks. The course is aimed at graduate students in STEM disciplines who are interested in computational methods and who have a basic grounding in real analysis. The class will involve both mathematical theory and algorithms.

Spr	APMA2822H	S01	26487	W	3:00-5:30(10)	(M. Ainsworth)

APMA 2980. Research in Applied Mathematics.
Section numbers vary by instructor. Please check Banner for the correct section number and CRN to use when registering for this course.

APMA 2990. Thesis Preparation.
For graduate students who have met the residency requirement and are continuing research on a full time basis.

Fall	APMA2990	S01	16535	Arranged	'To Be Arranged'
Spr	APMA2990	S01	25203	Arranged	'To Be Arranged'