



Operations Research &  
Financial Engineering

**The Academic Guide for Undergraduates  
Entering the Department in 2019-2020**

**Class of 2022**

**PRINCETON**  
School of Engineering and Applied Science



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## **Important Contacts**

### **Department Chair**

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### **The Undergraduate Office**

#### **Departmental Representative**

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229 Sherrerd Hall

#### **Departmental Assistants**

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## ORFE Academic Advisors

### Class of '20

Student	Advisor
<b>A-D</b>	Prof. John Mulvey, Room 207, x8-5423, mulvey@princeton.edu
<b>E-L</b>	Prof. R. van Handel, Fine Hall Room 227, rvan@princeton.edu
<b>M-SL</b>	Prof. Mengdi Wang, Room 226, x8-8773, mengdiw@princeton.edu
<b>SM-Z</b>	Prof. Amirali Ahmadi, Room 329, x8-6416, a_a_a@princeton.edu

### Class of '21

Student	Advisor
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<b>Q-Z</b>	Prof. Miklos Racz, Room 204, x8-8281, mracz@princeton.edu

### Class of '22

Student	Advisor
<b>A-E</b>	Prof. Alain Kornhauser, Room 229, x8-4657, alaink@princeton.edu
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<b>L-R</b>	Prof. Robert Vanderbei, Room 209, x8-2345, rvdb@princeton.edu
<b>S-Z</b>	Prof. Ronnie Sircar, Room 208, x8-2841, sircar@princeton.edu

## Department Web Page

Additional information on the department can be found at our web site: [orfe.princeton.edu](http://orfe.princeton.edu)

All ORFE department offices are located in Sherrerd Hall, except Prof. Ramon van Handel.

## An Introduction to the Department

Humankind has always faced significant challenges. With today's technology, however, we have the ability to collect vast amounts of data to illuminate the problems and opportunities we face. More importantly, we now can apply an array of robust analytical tools to deepen our understanding of the issues, to help us make better decisions and to develop solutions that will enhance our quality-of-life.

While collecting vast amounts of data is becoming easier, collecting the right data remains very expensive. How does one get from vast data to the right data? How should one analyze, understand and appropriately address uncertainty that is present in essentially all societal endeavors? And, how can one exploit these resources to make the best possible decisions and best contribute to an enhanced quality-of-life? These are precisely the questions that form the core of the Department of Operations Research and Financial Engineering. Problems of this kind have appeared for a long time in the understanding of logistics and management, energy, the environment, agriculture, the military and micro- and macro-economics. As our ability to handle more data and complexity has expanded, so has our ability to more deeply address traditional applications and venture to tackle new ones in finance, health care, biology and most aspects of our society. The basic mathematical modeling and analytic skills that lie at the heart of ORFE are now essential prerequisites to almost any quantitative discipline, including areas such as data science and statistics, information technology, energy resource management, health care, risk management, and many others. We view ORFE as the ideal quantitative education for the modern world, whether you see your future as a business leader, health care provider, legal/policy/political professional, data scientist, quantitative analyst, or academic researcher. Even poets might find something to love in ORFE.

ORFE is the intersection of six closely interconnected applied mathematical disciplines and application areas that lie at the heart of all activities in the Department: operations research, financial engineering, machine learning, optimization, statistics and probability. Each of these areas is described in more detail below.

### Operations Research

The field of operations research traces its foundations to World War II, although it includes dimensions that go as far back as the early days of the telephone at the beginning of the 20th century. It uses mathematical models and optimization methods to rigorously address quantitative problems in business and management, logistics, health care, energy systems, telecommunications, and transportation. The most common theme that runs through these problems is the efficient management of resources, where resources may be natural resources, economic resources, informational resources, equipment, people, and/or physical facilities. Students in operations research may follow a management track into business or consulting, or a more technical path into teaching, research, or software development. There is a burgeoning marketplace for sophisticated methods to schedule airlines and railroads or to optimize supply chains for large manufacturing and retail enterprises.

## Financial Engineering

Financial engineering uses mathematical models of financial markets to design innovative financial instruments and strategies to meet the specific needs of individuals and corporations, including managing risks and cash flows. To this end, financial engineers analyze and ultimately manage risks within an integrated framework, as compared with traditional piecemeal approaches. Often, new instruments are constructed based on the specific requirements of the investor. Solving these problems in a principled manner requires a combination of diverse analytical methods from applied mathematics, probability and statistics, stochastic processes and stochastic calculus, optimization, financial economics, and computation skills. Students grounded in financial engineering are in great demand: they find jobs on Wall Street and with traditional financial companies such as banks, insurance companies, mutual funds, and financial consulting companies, as well as in the CFO office within mainline corporations.

## Machine Learning

Machine Learning is a scientific field that aims to design computer programs and algorithms that can automatically learn from data and improve with experience. Machine Learning is routinely used to make fast and accurate predictions and decisions in problems whose scale is too large for humans to handle. Machine learning lies behind many recent technological advances such as self-driving cars, intelligent personal assistants, web search, credit risk analysis, customer preferences analysis and even genomics. At ORFE, we use mathematical tools to develop and analyze new Machine Learning algorithms to discover hidden structure in massive datasets and to make optimal decisions in the face of uncertainty and limited information.

## Optimization

Optimization is everywhere. Whether one talks about optimizing revenue, finding the best route to visit all the major cities of the United States, or optimizing the parameters of your new algorithm, there is a common thread: one wants to design procedures that can rapidly and accurately optimize a given function of interest. The area of mathematical programming is concerned with the design and analysis of such procedures. At ORFE we are particularly interested in large-scale time-varying optimization problems, involving substantial uncertainty and variability. Indeed these problems are more and more important in our "Big Data" era. We also pay special attention to the interplay between optimization and the domain specificity of the applications, whether it is finance, statistics or machine learning. The cutting-edge domain specific algorithms for large-scale optimization are nowadays critical to the success of most IT companies, this includes Google's search engine or Netflix's recommendation system.

## Statistics

Statistics is the science of learning from data. Learning what? Well, almost anything: Statistics are behind drug discovery, political campaigns, climate policies, genetic screenings, financial portfolio management and quality control to name only a few. If your senior thesis involves data, statistics will be your best friend. Statistics is a universal framework to make decisions based on data. In the “Big Data” era, statistics is more relevant than ever: it allows us to make predictions and understand the inherent uncertainty associated to these predictions. Moreover, using modern computer resources, statisticians have been able to contemplate richer models that fit better to reality and make ground breaking scientific discoveries, for example in understanding the human genome.

Hal Varian, the chief economist of Google, has famously said that the statisticians have the sexiest job of the 21st century. One advantage of working in statistics is that you can combine your interest with almost any other field in science, health, technology, or business. Most organizations now collect huge amounts of data and need statisticians to extract relevant information from them.

## Probability

Probability theory, also known as stochastics, is the mathematics of randomness and uncertainty. Probabilistic models lie at the heart of any application that involves uncertain outcomes, be it the arrival of patients and the availability of beds in hospitals, the fluctuations of financial markets, the spread of epidemics, the inheritance of genetic traits, and numerous other applications that span engineering and the sciences. They also provide the fundamental framework for modeling the structure of complex data, and form the foundation of statistical methods for analyzing text, speech, and biological data. At the same time, randomness can serve as an important resource for solving otherwise intractable problems, including simulation methods for estimating risks or for tracking and prediction in uncertain systems, random measurements for exploring customer preferences and for speeding up data acquisition in signal processing, and stochastic optimization algorithms for making optimal decisions on the basis of noisy data. Probability theory provides the tools needed to design and analyze such models and methods and to rigorously understand their behavior.



## Overview of the Undergraduate Academic Program

In addition to meeting the usual Engineering School requirements, students will complete courses in the following four groups:

- Departments core requirements (4 courses) – These form the intellectual foundation of our field, and cover statistics, probability, stochastic processes, and optimization.
- Departmental electives (10 or 11 courses depending on senior thesis choice) - These are additional courses that either extend and broaden the core, or expose the student to a significant problem area or application closely related to the core program.

### Independent Research

- Senior Thesis - ORF 478 - A full year effort that involves a major application of the techniques in the program applied to a topic that a student chooses in consultation with a faculty advisor. Students interested in a full-year senior thesis must be willing to spend the appropriate time during both the fall and the spring semesters. Students who are unable to make adequate progress can switch to ORF 479 and be required to take eleven departmental electives. Students will enroll in the spring and will receive credit for two course grades given in the spring.

### OR

- Senior Independent Project - ORF 479 (Spring semester only) - A short progress report will be due in January, (Dean's Date) to make sure that the students have chosen a suitable topic and matched up with their advisor. The final outcome will be a report due at the end of the spring semester. The report will fully describe the research project and its results. Typically projects will take approximately 30 to 50 pages. **(Also, students who take the independent project will need to take an additional 4XX ORFE departmental elective.)**
- Humanities and Social Science Electives (7 or more courses). B.S.E. students are required to include one course in at least *four* of the following six areas:
  - Epistemology and Cognition (EC)
  - Ethical Thought and Moral Values (EM)
  - Foreign Language at the 107/108 level or above (FL)
  - Historical Analysis (HA)
  - Literature and the Arts (LA)
  - Social Analysis (SA)

The University requires that 36 courses be taken to graduate. The School of Engineering requires math achievement through Math 202 (MAT 103, 104, 201 and 202, or equivalent), Computer Science proficiency (COS 126), Chemistry (CHM 201/202) and Physics (PHY 103, 104). Ten courses required to meet the engineering school requirement of 36 courses (more if the student places out of any of the SEAS requirements). Students are free to select these courses from any department, and are

expected to design an academic program with his/her advisor that produces a balanced education. No course may count under more than one heading, under any circumstances.

Each student selects and schedules courses in consultation with his/her academic advisor and the Departmental Representative. While generally no exceptions in the core courses are allowed, students may design specialized programs through their choice of departmental electives. Specialized programs must be approved by the Departmental Representative.

## **Graduate Courses**

You may take graduate courses for purposes of scholarly enrichment. In order to take them you must complete the "Permission for Undergraduates to Enroll in Graduate Courses" form with signatures from the course instructor, departmental representative, and Dean Bogucki. The completed form is submitted to the Office of the Registrar during open enrollment period. Graduate courses do not count towards departmental electives. You can find the necessary form here <https://registrar.princeton.edu/student-and-alumni-services/course-selection/adding-or-dropping-courses>

## **ABET Accredited Engineering Degrees**

The Department of Operations Research and Financial Engineering does not offer ABET-accredited engineering degrees. This has never been a problem for ORFE majors in their pursuit of post-graduate opportunities, and our B.S.E. degrees are fully accredited under Princeton University's overall accreditation. If, however, it is important that you major in an ABET-accredited program of study (e.g. for eligibility for an outside scholarship), please take this into account when choosing your major. Further information on which Princeton program of study are ABET-accredited, please consult the *Undergraduate Announcement*, <https://ua.princeton.edu/>.

## Academic Program Details

### SEAS Requirements

MAT 103, 104; COS 126; CHM 201 or 207; PHY 103 or 105, 104 or 106; MAT 201, 202 or 203, 204, or 217

### ORFE Requirements

#### Core Program (4 Courses)

##### ORF 245 Fundamentals of Engineering Statistics

A study of fundamentals of statistical methods and their applications in engineering. Basic concepts of probability, discrete and continuous distributions, sampling and quality control, statistical inference, empirical models, and least squares. Prerequisite: Mat 201 taken concurrently, prior to, or equivalent.

##### ORF 307 Optimization

Model formulation, analysis, and optimization of deterministic systems. Introduction to quantitative methods: linear programming, duality theory, large-scale mathematical programs, and network analysis. Emphasis will be on applications to problem areas such as allocation of resources, transportation systems, scheduling, capital budgeting, and network problems. Two 90-minute lectures. Prerequisite: MAT 202. It is strongly recommended that COS 126 or equivalent be taken prior to or concurrently with this course.

##### ORF 309 Probability and Stochastic Systems

An introduction to probability and its applications. Random variables, expectation, and independence. Poisson processes, Markov chains, Markov processes, and Brownian motion. Stochastic models of queues, communication systems, random signals, and reliability. Prerequisite: MAT 201, or instructor's permission.

##### ORF 335 Introduction to Financial Mathematics (also ECO 364)

Financial engineers design and analyze products that improve the efficiency of markets and create mechanisms for reducing risk. This course introduces the basics of financial engineering: the notions of arbitrage and risk-neutral probability measure are developed in the case of discrete models; Black-Scholes theory is introduced in continuous-time models, and interest rate derivatives and the term structure of interest rates are discussed. Prerequisites: MAT 104, ORF 309.

## Department Electives (10 or 11 Courses)

The departmental electives represent courses that further develop a student's skills in mathematical modeling either by a more in-depth investigation of core methodologies, applying these skills in specific areas of application, or learning about closely related technologies. Students must choose ten courses from the following list, with the following constraints:

- There must be at least four courses from ORFE
- There can be no more than three courses from any one department (excluding ORFE)

All departmental electives:

- ORF 311 – Stochastic Optimization and Machine Learning in Finance
- ORF 350 – Analysis of Big Data
- ORF 360 – Decision Modeling in Business Analytics
- ORF 363 – Computing and Optimization for the Physical and Social Sciences
- ORF 375/376 - Junior Independent Work
- ORF 401 - Electronic Commerce
- ORF 405 – Regression and Applied Time Series
- ORF 406 - Statistical Design of Experiments
- ORF 407 – Fundamentals of Queueing Theory
- ORF 409 - Introduction to Monte Carlo Simulation
- ORF 411 – Sequential Decision Analytics and Modeling
- ORF 417 - Dynamic Programming
- ORF 418 - Optimal Learning
- ORF 435 - Financial Risk Management
- ORF 455 – Energy and Commodities Markets
- ORF 467 – Transportation Systems Analysis
- ORF 473/474 - Special Topics in Operations Research and Financial Engineering
- CEE 304 – Environmental Engineering and Energy
- CEE 460 - Risk Analysis
- CHM 301 – Organic Chemistry I
- CHM 302 – Organic Chemistry II
- COS 217 - Introduction to Programming Systems
- COS 226 - Algorithms and Data Structures
- COS 323 - Computing for the Physical and Social Sciences
- COS 340 - Reasoning about Computation
- COS 402 - Machine Learning and Artificial Intelligence
- COS 423 - Theory of Algorithms
- COS 425 – Database and Information Management Systems
- COS 485 – Neural Networks: Theory and Application
- ECO 310 - Microeconomic Theory: A Mathematical Approach
- ECO 311/312 – Macroeconomics: A Mathematical Approach
- ECO 317 - The Economics of Uncertainty

- ECO 332 – Economics of Health and Health Care
- ECO 341 - Public Finance
- ECO 342 - Money and Banking
- ECO 361 - Financial Accounting
- ECO 362 - Financial Investments
- ECO 363 - Corporate Finance and Financial Institutions
- ECO 418 - Strategy and Information
- ECO 462 - Portfolio Theory and Asset Management
- ECO 464 - Corporate Restructuring
- ECO 466 - Fixed Income: Models and Applications
- ECO 467 - Institutional Finance
- EEB 324 – Theoretical Ecology
- ELE 301 – Designing Real Systems
- ELE 381 – Networks: Friends, Money and Bytes
- ELE 485 – Signal Analysis and Communication Systems
- ELE 486 – Transmission and Compression of Information
- ENV 302 – Practical Models for Environmental Systems
- MAE 206 – Introduction to Engineering Dynamics
- MAE 345 – Introduction to Robotics
- MAE 433 - Automatic Control Systems
- MAE 434 – Modern Control
- MAT 320 - Introduction to Real Analysis
- MAT 322/APC 350 – Introduction to Differential Equations
- MAT 375 - Introduction to Graph Theory
- MAT 377 - Combinatorial Mathematics
- MAT 378 - Theory of Games
- MAT 385 - Probability Theory
- MAT 391/MAE 305 - Mathematics in Engineering I or MAT 427, (both may not be taken because content is too similar)
- MAT 392/MAE 306 - Mathematics in Engineering II
- MAT 427 - Ordinary Differential Equations
- MAT 486 - Random Process
- MAT 522 - Introduction to Partial Differential Equations
- MOL 345 – Biochemistry
- MOL 457 – Computational Aspects of Molecular Biology
- NEU 437 – Computational Neuroscience
- NEU 330 – Computational Modeling of Psychological Function
- PSY 360 – Computational Models of Cognition

Students often wish to follow a theme in their selection of courses. Below are a few possible themes:

- Applied Mathematics: MAT 375, 378, 321; MAE 406; ORF 405
- Engineering Systems: ORF 409,467; COS 226, 323; ELE 301; MAE 433
- Financial Engineering: ORF 311, 350, 405, 435; ECO 362, 465
- Information Sciences: ORF 401, 418; COS 217, 226, 425
- Machine Learning: COS 217, 226; ORF 350, 407, 411, 418
- Pre-Med/Health Care: CHM 301, 302; MOL 345; ORF 350, 401, 411, 418
- Statistics: ORF 311, 350, 409, 418, 405, 467

### Junior Independent Work (Optional)

Students selecting Junior Independent Work need to prepare a proposal including the following:

1. Title
2. 100 word abstract/literature. Abstract will describe the problem, why it is important, why you want to study it and what you hope to have accomplish by the end of the semester
3. "Syllabus" containing weekly readings and work plan. What you will focus on and what you plan to accomplish in each week of the semester.
4. Table of contents of the final report that you will prepare that will form the basis of the grade that you will receive.
5. Find a faculty member that will supervise you in the pursuit of the above.
6. Obtain Departmental Representative's approval of what you have put together in response to the above.

The proposal and signed Junior Independent Study Form must be submitted to [tzigler@princeton.edu](mailto:tzigler@princeton.edu) prior to enrollment during the registrar's open enrollment period. The requirements for satisfactory completion of the study (such as reports, examinations, etc.) are set by the faculty mentor, not the Department, and the student should be clear about them when the work is begun.

## Senior Independent Work

### Senior Thesis (ORF 478)

This begins in the spring semester in the junior year, with a selection process to insure that students are matched with a faculty member based on the preferences of the students.

Students interested in a full-year senior thesis must be willing to spend the appropriate time during both the fall and the spring semesters. Two course grades will be given in the spring.

Students who are unable to make adequate progress can switch to the Senior Independent Project (below) and be required to take eleven departmental electives.

Three reports are required leading up to the final thesis report. The first is due in September, the second in November, and the third in February. The research results will be presented to faculty and students at the end of the spring semester. For more information refer to the senior thesis guide on our website <https://orfe.princeton.edu/documents/senior-thesis-guide>

**OR**

### Senior Independent Project (ORF 479, Spring Semester Only)

Students will choose an advisor during junior year, spring semester, based on the usual arrangement – attending presentations by the ORFE faculty, reading the Faculty Interests Guide and meeting with individual faculty members. Students will select a broad topic, and rank faculty according to their preferences.

A short progress report will be due in January, (Dean's Date) to make sure that the students have chosen a suitable topic and matched up with their advisor. The final outcome will be a report due at the end of the spring semester. The report will fully describe the research project and its results. Typically projects will take approximately 30 to 50 pages. Also, students who take the independent project will need to take an additional 4XX ORF course, for a total of eleven electives.

## Typical Course Schedule

FRESHMAN YEAR		SOPHOMORE YEAR	
FALL	SPRING	FALL	SPRING
1. CHM 201/207-General Chemistry 2. MAT 104 Calculus 3. PHY 103 General Physics 4. Writing Requirements 5.	1. COS 126 Gen. Comp. Sci. 2. MAT 201 Multivariate Calc 3. PHY 104 General Physics 2 4. (ORF 245 Fund. Of Eng. Stats) 5.	1. ORF 245 Fund. of Eng. Stats 2. MAT 202 Linear Algebra Appl. 3. Departmental Elective 4.(ORF 309 Probability/Stat Systems) 5. (ECO 310 Microecon Theory)	1. ORF 307 Optimization 2. ECO 310 Microecon Theory 3. (ORF 309 Probability/Stat Systems) 4.( ORF 335 Intro Fin. Mathematics) 5.
JUNIOR YEAR		SENIOR YEAR	
FALL	SPRING	FALL	SPRING
1. ORF 309 Probability/Stat Systems 2. Departmental Electives 3. Departmental Electives 4. 5	1. ORF 335 Intro Fin. Mathematics. 2. Departmental Electives 3. Departmental Electives 4. 5.	1. ORF 478 Sr. Thesis (or Depart) 2. Departmental Electives 3. Departmental Electives 4. 5.	1. ORF 478/479 Sr. Thesis 2. Departmental Electives 3 4. 5.

(Alternate schedule)



## Elective Checklist

DEPARTMENTAL ELECTIVES (10 or 11 courses - all graded)					
(If course is not from recommended list, provide explanation and obtain approval from Departmental Representative)					
Course	Check	Area (see below)	Course	Check	Area (see below)

HUMANITIES AND SOCIAL SCIENCE ELECTIVES (7 or more courses)					
Course	Check	Area (see below)	Course	Check	Area (see below)

## Departmental GPA, Graduation Requirement, Honors and Prizes

**Departmental GPA:** Prior to graduation, the department will calculate each student's *Departmental Grade Point Average* (GPA). The Departmental GPA is computed as the average of 15 grades. For students choosing the 2-semester Senior Thesis option (ORF 478) the 15 grades are: the thesis, the best ten qualified departmentals, plus each of the core courses except ORF 245. To be a qualified departmental the courses must satisfy the following constraints: must be a member of the departmentals electives list (pages 8 & 9) in the Academic Guide, no more than three can be from one department. Each of these courses must have been taken for a grade at Princeton (meaning no PDF). Courses taken at other institutions will not be counted. If 15 graded courses meeting the criteria do not exist because some requirement was met with courses taken at other institutions, then other technical graded courses taken at Princeton will be used to calculate a GPA.

For students choosing the 1-semester Senior Independent Research option it is the same as above with an additional ORF 4XX departmental, totaling 11 departmentals. Note, while two 200-level courses may be included among the Departmental Electives, no 200-level courses are counted in the departmental GPA (except COS 217, COS 226, and MAE 206).

A minimum 2.0 Departmental GPA is required for graduation. The departmental GPA is a significant factor but not sole determinant of honors. The overall academic quality of the entire ORFE class and academic performance in individual classes is also taken into account in the faculty's decision in awarding honors.

**Graduation Requirement:** Core Courses and Departmental Electives **may not be taken on a PDF (Pass, D, Fail) basis**. Equivalent versions may be taken at other Universities but require prior formal written permission. Grades received in courses taken at other universities are not included in the computation of the departmental GPA. A passing grade must be received in each ORFE Core Course and each Departmental Elective. To graduate, a student must satisfy the University's 36 course requirement, the SEAS requirements for Physics, Chemistry, Math and Computer Science, ORFE's Core and Departmental Elective requirement and achieve a Departmental GPA of 2.0 or greater.

**Honors:** Highest Honors, High Honors and Honors are awarded by the ORFE faculty to those graduating seniors who have demonstrated the highest levels of academic achievement. Departmental GPA is the major criterion; however, each student's overall academic record and overall quality of the entire class are also considered in the awarding of these honors.

**Prizes:** The ORFE faculty also awards a few individual prizes for specific superior achievement in a few defined categories.

## Other Program Opportunities

**Certificates of Interest to ORFE Students:** The following certificate programs complement well with ORFE and are thus popular with students:

- Applications of Computing
- Engineering Management Systems
- Environmental Studies
- Finance
- Program in Applied and Computational Mathematics
- Program in Robotics and Intelligent Systems
- Statistics and Machine Learning
- The Woodrow Wilson School

## Taking Courses at Other Schools

Students may take courses at other schools during the summer, during a semester off, or during a year abroad. The rules are slightly different depending on the activity. If you are considering taking a replacement course during the summer or a semester off, you need to obtain a form from West College where you describe the course that is being taken, and what course at Princeton is being replaced. This is particularly important if you want the course to count toward some requirement. Read the form carefully. It requires that you obtain the approval of the *home* department (or the professor that teaches the equivalent Princeton course) for the course. For example, if you wish to take a replacement course for MAE 305, you should get the signature of the instructor teaching MAE 305 or the Departmental Representative from MAE. A replacement for an ORFE course requires the signature of the Departmental Representative of ORFE. Approval that the course is equivalent or better than the Princeton course, that is to replace, must be obtained by the Professor teaching the Princeton course. Once received approval can be granted by the Department Representative. Please provide a syllabus or at least a detailed description of the course before obtaining approval.

If you wish to take a semester or a year abroad, you need to obtain the signature of the Departmental Representative of ORFE, in addition to the approval of the course of study committee.

Note, core courses (except for ORF 245) may not be taken at other schools without special dispensation by the Department Representative. They must be taken at Princeton and must be taken "graded". Departmental electives, if approved before taking, may be taken at other schools; however, the grade earned will not be included in any GPA calculation.

## **Faculty and Their Research Interests**

### **Amirali Ahmadi, Assistant Professor**

Research interests are broadly in optimization and systems theory with an emphasis on algorithms and efficient computation. Particular focus on design of algorithms for problems defined by polynomial inequalities and arising in operations research, engineering, and statistics. Specific areas of research include semidefinite programming, algebraic methods in optimization and control, Lyapunov analysis of dynamical systems, computational complexity, and approximation algorithms for intractable problems in continuous and combinatorial optimization.

### **Rene A. Carmona, Professor**

Stochastic analysis, stochastic control and stochastic games, especially mean field games. High frequency markets, environmental finance and energy and commodity markets.

### **Erhan Çinlar, Professor Emeritus**

Stochastic models of random phenomena in engineering, finance, and operations research. Control and optimization of stochastic systems. Theories of queues, inventories, reliability, and replacement. Point processes, Markov processes, stochastic differential equations.

### **Jianqing Fan, Professor**

Research interests focus on statistical machine learning and big data and their applications in finance, biological science and health sciences. They include Finance, Computational biology, machine learning, time series, and other statistical theory and methods.

### **Alain L. Kornhauser, Professor**

Development and application of operations research and other analytical techniques in various aspects of Autonomous Vehicles, aka "SmartDrivingCars", including

- The fundamental design of computer vision techniques for for the rapid classification and identification of the driving environment, especially "deep learning convolutional neural networks",
- Analysis and classification of collision-free driving scenarios,
- Quantification of accident risk and the investigation, formulation and design of "pay-as-you-drive, pay-as-the-car-drives" insurance,
- Investigation and creative design of the human-computer interfaces for SmartDrivingCars
- Operational and feasibility analyses of autonomousTaxi (aTaxi) systems

### **William A. Massey, Professor**

Queueing theory, dynamic rate queues, stochastic networks, dynamical systems, optimal control, communication networks and healthcare management.

### **John M. Mulvey, Professor**

Expert on optimization under uncertainty, with emphasis on financial planning applications. Develops strategic planning systems for financial organizations, such as American Express, Towers Perrin - Tillinghast, Merrill Lynch and Siemens. Interested in the optimization of large organizations by means of decentralized optimization methods. Current research involves optimizing multi-strategy hedge funds. Apply novel methods in machine learning to financial planning systems.

### **Warren B. Powell, Professor**

Warren Powell is interested in optimization under uncertainty spanning a wide range of problem classes, motivated by applications in energy, health, transportation, business analytics, and laboratory sciences. His approach draws on a unified modeling framework, with an emphasis on computation. This framework approaches sequential decision problems by identifying and testing the best out of four classes of policies. This work requires an accurate model of the different types of uncertainty that arise in different applications. Careful assessment of risk is an important dimension. For more information, please see <http://www.castlelab.princeton.edu>

### **Miklos Z. Racz, Assistant Professor**

My research focuses on probability, statistics, and its applications. I am interested in statistical inference problems in complex systems, in particular on random graphs and in genomics. I am also interested more broadly in applied probability, combinatorial statistics, information theory, control theory, interacting particle systems, and voting.

### **Mykhaylo Shkolnikov, Assistant Professor**

Stochastic portfolio theory, optimal investment, stochastic analysis, interacting particle systems, random matrix theory, large deviations, markov chains.

### **Ronnie Sircar, Professor**

Financial Mathematics & Engineering; stochastic models, especially for market volatility; optimal investment and hedging strategies; analysis of financial data; credit risk; dynamic game theory and oligopoly models; energy and commodities markets.

### **Ludovic Tangpi, Assistant Professor**

Financial mathematics (risk management, model uncertainty, optimal investment); Stochastic analysis; stochastic control, Probability theory (optimal transportation, functional inequalities); Statistical and numerical methods in finance (data analysis, numerical simulations).

### **Robert J. Vanderbei, Professor**

Algorithms for, and applications of, linear and nonlinear optimization. Applications of special interest include high-contrast imaging, orbital dynamics/mechanics, parametric linear programming as it arises in, say, machine learning, and parameter estimation under sparse sampling as it arises for example in generating level-of-difficulty measures.

### **Ramon van Handel, Associate Professor**

I am broadly interested in probability theory and its interactions with other fields. Probability theory, i.e., the study of randomness, is a very rich subject: it combines many different types of mathematics, and is used to solve a surprisingly diverse range of problems in different fields. I am particularly fascinated by the development of probabilistic principles and methods that explain the common structure in a variety of pure and applied mathematical problems.

### **Mengdi Wang, Assistant Professor**

Stochastic optimization, decision making under uncertainty, reinforcement learning, optimization in learning, optimization in statistics and finance applications.

## Research and Teaching Studios

Students in the department often participate in the research interests of the faculty, and may take advantage of the facilities used for this work. This includes:

- CASTLE Labs specializes in computational stochastic optimization and learning, with applications in energy (primarily), business processes, transportation and logistics, and health. Most of the undergraduate research focuses on mathematical models and algorithms for energy systems, spanning topics such as integration of renewables, pricing of energy contracts, pricing, demand response, energy challenges in international settings, and energy markets. Some students get involved in purely algorithmic challenges, advancing the state of the art in approximate dynamic programming, stochastic search and optimal learning. To learn more about CASTLE Lab, see its web page: <http://www.castlelab.princeton.edu>. Be sure to visit the PENZA website for energy research at <http://energysystems.princeton.edu>. The Financial Engineering Studio provides students with access to financial data support research into methods for managing risk. Research topics include the development of advanced financial instruments which can be used by insurance companies, major manufacturing companies and investment houses to control risk exposure.
- The Financial Econometrics Studio works on a variety of quantitative problems from finance using statistical techniques and financial economic theory. These include valuation of financial derivatives, optimal portfolio allocation, risk modeling and management, volatility estimation, modeling and analysis of financial data, and simulation of financial system. The studio also studies financial econometrics theory and provides various fundamental insights into the statistical inference problems from financial markets.
- The Statistics Studio studies statistics theory and methods with focus on high-dimensional statistics, biostatistics, nonparametric techniques, and large-scale statistical computing. The studio engages cutting-edge research on statistical modeling from various problems in machine learning, biomedical studies, computational biology, analysis of Big Data, network data, and financial data. It designs statistical methods and algorithms for these modeling issues and provides fundamental understanding and theoretical foundation on statistical and computational efficiency of these methods and algorithms. This expands into other scientific frontiers where the statistics discipline is useful.
- The Transportation Center conducts research on information and decision engineering technologies and how these technologies can be used to improve transportation related decision making.

## Career Paths

### Updates from Recent ORFE Graduates

#### Meghan Fehlig, '02

I'm working as a transportation engineer in the transportation planning department at Parsons Brinckerhoff (Princeton, NJ office). I became interested in this field after taking Prof. Kornhauser's transportation course and doing senior thesis research on the traffic woes of the Route 1 Corridor. Rarely a day goes by that I don't rely on something I learned during my thesis research or ORFE courses, be it traffic condition analysis, general research skills, MS Excel work, or NJ transportation history. A real bonus about being in this field with an ORFE degree is having a solid background in economics. Many of the exciting transportation innovations are market-based solutions and my ORFE studies have uniquely positioned me to work on these innovations with a different approach from my civil engineer and urban planner colleagues.



#### Daniel Nash, '03



I am a Director of new Growth Platforms at Avery Dennison, a \$6.5 billion dollar manufacturing and consumer products company with expertise in pressure-sensitive technology, and retail branding and information solutions. As such, I am responsible for identifying and building new growth opportunities for the company. For the past year, I have focused on the healthcare industry, working to leverage Avery Dennison's RFID technology to improve key processes in hospitals. Prior to Avery Dennison, I worked as a consultant for the Boston Consulting Group serving in both the Singapore and Boston office, and in the Corporate Finance department of The Walt Disney Company. I received my MBA from Harvard Business School in 2008.

My ORFE education continues to provide a significant advantage relative to my peers. The ORFE department taught me how to quickly identify the key drivers of a new market or successful product launch, so that I can efficiently validate my assumptions and limit my downside risk. I believe there is no better education for a successful career in business.

#### Katherine Milkman, '04

After completing my ORFE degree, I received a Ph.D. from Harvard University's joint doctoral program in Computer Science and Business. I am now an assistant professor at the Wharton School at the University of Pennsylvania where I teach undergraduates and MBAs about decision making and behavioral economics. When I'm not in the classroom, I spend my time on research that documents various ways in which individuals systematically deviate from making optimal choices. I am particularly interested in understanding what factors lead people to undersave for retirement, exercise too little, eat too much junk food, and watch too many lowbrow films. Recently, I have also begun to study race and gender discrimination, focusing on how a decision's context can alter the manifestation of bias. I have published articles in leading academic journals such as *Management Science* and the *Proceedings of the National Academy of Sciences*, and my work has been featured by numerous media outlets including *The New York Times*, *BusinessWeek*, *The Economist*, and *NPR*. In 2011, I was recognized as one of the top 40 business school professors under 40 by *Poets and Quants*.





### **Kimberly Mattson, '05**

I am an Investment Associate at Bridgewater Associates, an institutional hedge fund manager in Westport, CT. We deal with large institutions - pension funds, college endowments, central banks. Most of my work revolves around solving problems that deal with portfolio structuring. I use a lot of the concepts I learned in ORFE in my day-to-day work. I use a lot of the portfolio math I learned in ORF 435 to figure out a portfolio's risk and return characteristics. We also have a tool that calculates a client's optimal portfolio using a Monte Carlo simulation process. I've even used some of the ideas I developed in my senior thesis, which used implied volatility in currency options to estimate the chance of a currency crisis, in my job, since Bridgewater manages currencies and options as part of its investment strategy. In my opinion an ORFE degree is the most flexible major to have at Princeton because it teaches a wide array of skills to apply basically anywhere after college.



### **Jacqueline Ng, '06**



Since graduating as an ORFE in 2006, I have worked in a variety of roles that have drawn upon the knowledge and skills I gained as an ORF major. After graduation, I spent nearly 6 years at Morgan Stanley, where I worked in US Government Bond Trading, Sales & Trading Strategy and US Equity Research. During my time at Morgan, I also pursued an executive-MBA at Columbia University. I recently left Morgan Stanley to work for Microsoft in a strategy and finance type position for their consumer advertising support business.

My undergraduate degree in ORFE has aided me tremendously in each one of my job functions. At a high level, my ORF classes taught me how to think quantitatively and analytically – which has been a versatile skill that has helped me grasp new concepts quickly in the workplace. The vigorous ORFE curriculum prepared me well for the challenges of the workplace, and has given me confidence when faced with complex problems.

On a more specific level, I find myself constantly drawing upon the knowledge I gained in my ORFE classes. For example, Professor Sircar's ORFE 335 class (Introduction to Financial Engineering) taught me about various fixed income products and pricing models. As a bond trader, I frequently used similar pricing models on a day-to-day basis, in addition to various probability models, statistics and historical regressions. Additionally, my undergraduate classes prepared me well for business school, where my solid foundation in operations facilitated my understanding of our operations management MBA coursework. Finally, in my current role at Microsoft, I find that the knowledge I've gained as an ORF major accompanies me both directly and indirectly in every challenge and problem I face in the workplace.

### **Raj Hathiramani, '07**

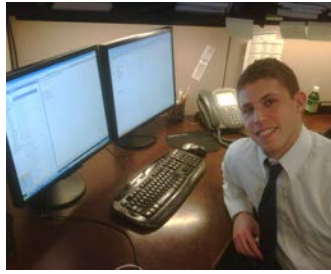


Since graduating in 2007, I have worked in a few different roles that have drawn upon valuable concepts I learned from the ORFE program. I spent about 4 years working at Citadel Investment Group, first in quantitative research and derivatives trading and later in fundamental long/short equities, covering financial services. ORFE courses in financial engineering and asset pricing were instrumental in understanding how to value both stocks and derivatives.

After Citadel, I started working at Google, helping lead the sales strategy and financial analytics for the company's display advertising products. Prof. Carmona's class on regression and applied time series enabled me to use R and SQL to analyze and set targets for Google's revenue growth and present business insights to senior management.

Inspired by my managers at Google, I decide to pursue an MBA at Wharton, where I am currently a first year student. While at Wharton, I have also been working part-time as a portfolio consultant at First Round Capital, a seed-stage venture capital fund, conducting strategy projects for portfolio companies and assisting with diligence for the firm's potential investments.

### **Zachary Kurz, '08**



I am working as an investment banking analyst in Morgan Stanley's Mergers & Acquisitions Group. I am responsible for building financial models in Excel and creating presentations for our senior bankers to present to the Firm's clients. I have been part of some really interesting transactions, including the recent \$46 billion merger of Merck and Schering-Plough, two large pharmaceutical companies. I frequently use a lot of the math skills I learned as an ORFE major and the rigorous foundation has definitely given me a leg up on other young people at the Firm. In particular, a lot of the programming skills I acquired at Princeton have been incredibly useful. I am still unsure about where my career is headed but I am eager to further immerse myself in the financial world.

**Jonathan Lange, '09**

I am an associate in the private equity group at Bain Capital. We invest in market-leading companies in a wide range of industries and try to optimize operations during our ownership. In my first year, I have evaluated several interesting potential transactions, primarily in media and technology. Prior to Bain Capital, I spent two years as an analyst in the Technology, Media, and Telecommunications investment banking group at Goldman Sachs, where we advised companies on mergers, acquisitions, IPOs, and other financing transactions. Through my roles at Goldman Sachs and Bain Capital, I have had the chance to travel to across North and South America and work directly with management teams, both as an advisor and investor. My ORFE education definitely gave me a great foundation in financial modeling and has been a huge advantage as I work through the theoretical aspects of valuation and the financial impacts of potential transactions.



**Kate Hsieh '10**



At Princeton, I studied an interdisciplinary curriculum that treaded not only in ORFE courses, but also in the natural sciences, global health, and even the humanities. My goal was the develop a holistic understanding of quantitative and qualitative approaches to interpreting and solving real world problems. After graduating in 2010, I worked as a Princeton ReachOut56-81 International Fellow with Wellbody Alliance (formerly Global Action Foundation), a global health NGO focusing on sustainable community-based health interventions in the rural diamond-mining district of Sierra Leone. There, I was involved in a wide range of projects including HIV home-based care, reproductive health peer education, social entrepreneurship in agriculture, amputee health, primary care in resource-limited environments, and more. I also learned about what it takes to operate a startup in this field and about the challenges and complexities of navigating in a developing environment with different cultural and professional norms. In addition to working in the NGO space, I became interested in ethnography in Sierra Leone, particularly on the topic of female genital cutting. This year, I am studying a Master of Science degree in Medical Anthropology at the University of Oxford prior to returning to the US for medical school.

While I have not directly applied many of the mathematical skills I learned in my ORFE core courses, my engineering training is omnipresent in managing my day-to-day operations. It shapes the way that I think, analyze, and organize my thoughts when presented with new problems or projects. Moreover, I have found that my ORFE degree and unusual academic and extracurricular background has been an asset in finding internship or employment opportunities because it allows me to bring unique insights to the table. ORFE teaches students to model real-world situations and make optimal and efficient decisions under uncertainty or with limited information - these tools are necessary in virtually any field, particularly in healthcare or global health. I encourage students to consider using their ORFE education to pursue unconventional careers, as it may open doors to greater responsibility and intellectual creativity. I am happy to connect any students interested in the healthcare, international development, or medical anthropology.



**Chetan Narain '11**

I'm working at Google on the Search Ads Quality team, which is responsible for deciding which ads to show on the search result page and thus brings in the majority of Google's revenue. The job is a blend of engineering, computer science, and mathematics, which is exactly what ORFE is all about. I've worked on projects where we try to predict how many people will click on an ad, something that requires substantial data crunching, strong mathematical analysis, and a good understanding of how people's minds works. My position is right at the confluence of mathematics, finance, and computer science, and was a natural extension of the similarly multifaceted education I got in the ORFE program.

### Anna Zhao '12

I work at the NBA League Office in the basketball operations department. My department functions like the government of basketball, as we oversee the on-court activities, manage rule changes, and address any questions or concerns from teams. My most direct ORFE project has been when I used my foundation in probability (ORF 309!) to evaluate teams' drafting abilities (not gonna lie, I was pretty excited about this). Most of my time has been spent on performing statistical analysis on a variety of areas, such as injuries, the NBA Draft, and the NBA Development League. Even when my job has no math involved, like stuffing All-Star Game gift bags, what I learned about operations research helps increase efficiency. I'm glad that I switched to ORFE because I learned how to approach solving complex problems in real-world situations, how to code to manipulate raw data into a useful form, and how to complete tasks efficiently.



### Nathan & Natalie Keys '12



Natalie: After graduation I worked for Liberty Mutual Insurance as an actuarial analyst. Some of my favorite projects were creating statistical models of cost-saving initiatives in the claims handling department, finding root causes of financial or operational trends and developing predictive models, and assessing profitability for several lines of business in different states.

ORF 309 and ORF 335 were directly applicable, as the material is in several of the first actuarial exams. ORF 407, 409, 467, and 411 acted as capstone courses - they gave me practice applying fundamental probability and statistics, and a level of comfort with complex systems and

processes.

At the beginning of 2015 I joined a startup developing anti-collision technology for heavy vehicles. I work from a Joint Venture office in China, doing data analysis and programming.

Nathan: As an ORFE student, I drew many of my departmental electives from the Computer Science department. After graduating I started working for a small marketing analytics company in Seattle that builds and operates omni-channel marketing campaigns large retailers. My role was two-fold: first, I worked on the user interface team that developed the web applications that our clients used to set parameters on their marketing campaigns and evaluate their results through a rich reporting and data analytics portal. Second, I participated in "productionalizing" prototype code that the research team had written on our Hadoop big-data analytics platform to help generate the data that was ultimately presented in our user interface tool.

Most recently I have worked for a start-up company in China that is developing anti-collision technology for heavy vehicles. My role encompasses both directing and participating in technical product design and development. In this role I supervise a team of developers, from orienting them in our project, to defining, prioritizing, and assigning tasks to them, in addition to working alongside them as a fellow developer.

### **Malavika Balachandran '13**

I am working as an Analyst in the Securities Division at Goldman, Sachs & Co. My team is responsible for structuring derivative products for private individuals; I spend most of my day working with clients, providing them with pricing on derivative packages, pitching trade ideas that meet their investment objectives, and explaining how these complex financial products work. It was through my ORFE education, particularly my coursework in Financial Math, that I gained a strong foundation in derivatives pricing theory, which governs the valuation of the products I structure and sell. While I am not solving stochastic calculus problems or developing pricing models every day, understanding how the underlying pricing models work and how a position's risk and price changes with respect to the input variables is extremely valuable in my job. My interest in math and computer science attracted me to the department, where I developed a strong intellectual interest in derivatives pricing and computational finance, and I am very lucky that I have the opportunity to apply my knowledge and passion in my career.



### **Adam Esquer '14**



After completing my ORFE degree in 2014, I began interning with the Tampa Bay Rays almost immediately after school. I then signed on with the team in a fulltime capacity later that year. I am a member of the Rays' Research and Development Department. Being in a division with some of the biggest market teams in the league (the Boston Red Sox and New York Yankees), it is crucial that we maintain our edge in analytics to continue to compete and succeed while only being able to sustain a payroll that is one quarter that of our competitors. The Rays have always been at the forefront when it comes to creating and applying new methods of player valuation and on-field strategy, and it is an honor to now consider myself a part of this group. The work that we do affects everything from trades and signings to defensive alignment and other strategies on the field. There is nothing more rewarding than seeing the work that you do directly affect decisions that are being made.

Looking back, I can think of no better course of study than ORFE to prepare oneself for the sports industry. I think ORFE provides an invaluable combination of having a strong theoretical background and the technical skills to apply this more abstract understanding to real world problems. From covering applied regression to simulation, ORFE got me well ahead of where I needed to be to break into the sports industry and succeed. The truth is that an ORFE degree can be applied in any industry. ORFE is all about optimizing decision-making, and that basic idea is pertinent to any front office of any company that you will ever come across.

## **Class of 2018 Senior Thesis Titles**

*Analysis of the Federal Reserve's Quantitative Easing Program: Asset Price, Yield Curve, & Liquidity Effects*

*Economic, Environmental and Political Impacts on Crude Oil Price Volatility*

*Multi-Task Learning for Photoplethysmographic Measurement of Heart Rate*

*The Clutch Factor Quantifying NBA Performance When It Matters Most*

*A Future for American Mobility: A Case for Shared Autonomous Vehicle Adoption Through a Taxi Network Optimization*

*Approximate Dynamic Programming: Designing an Economically Optimal Fleet of Electric Self-Driving Cars*

*Maximize Safety, Minimize Cost: A Long Term Solution to Syrian Refugee Crisis through Optimization*

*Rail in the Age of Autonomous Ridesharing: Analysis of a Hybrid Transportation Demand Model*

*Valuation: A Dynamic Time Warping Approach to Sentiment Time Series Classification*

*Tell Me What You Think: Incorporating Insights About Consumer Behavior into Predictions of Economic Activity*

*Game of Shows: Using Linear Regression and Integer Programming to Optimize Television Ratings*

*Predicting Changes in Crude Oil Futures Spreads Using High Frequency Order Flows*

*Analyzing the Political Leaning of Electronic Media with regards to its Coverage of South Asia: A Machine Learning Approach*

*Discrimination in the Criminal Justice System: A Mechanism for Balancing Misclassification by Race*

*Nowcasting: Predicting Demographics and Crime with Facebook Ad Data*

*Modelling the hippocampus with leabra7, a new tool for simulating massively recurrent, biologically realistic neural networks*

*A Game Theoretical Approach to Cap and Trade System Modeling and Auction Design*

*Classifying News, Satire, and "Fake News": An SVM and Deep Learning Approach*

*Analyzing the Effects of the New Stratified Methodology on HRRP Penalty Allocation*

*Portfolio Optimization Through Wisdom of the Crowd*

*Show Me the Money: Utilizing Applied Time-Series to Increase Credit Access for Small and Medium Businesses in Nigeria*

*A Cross-Sectional Characterization of Risk-Neutral Option-Implied Probability Distributions*

*Volatility-of-Volatility: Dynamic Models and Hedging Strategies*

*Deep Coaching: A Deep Learning Approach for Human Action Recognition in Photos and Videos of Athletic Motions*

*Optimal System Design for Multi-Agent Peer-to-Peer Energy Trading Networks*

*Empirical Analysis of Cryptocurrency Volatility*

*Learning to Earn: An Application of Reinforcement Learning to High-Frequency Trading in the U.S. Futures Market*

*Identifying the Most Suitable Counties in America for Residential Ride-Sharing and Real Estate Growth Potential: A Quantitative, Geographical, and Financial Approach*

*Effective & Effectively Trading Information: Exploring the Extent to Which Continuing Disclosures Affect the Secondary Market for Municipal Securities*

*A National Parallelized Hybrid Activity/Agent-Based Demand Model to Characterize the Mobility of the United States*

*A Vector Autoregression, Machine Learning, Regime-Based Analysis of Swap Spread Determinants*

*Leave Me a Loan: Machine Learning Strategies for Loan Portfolio Management*

*Analysis of Regimes in Housing and REIT Markets: 1997 - 2017*

*An Analysis of Counterparty Credit Risk Estimation Methods Using Monte Carlo Simulation*

*Novel results on computational methods for polynomial optimization*

*Making Lemonade Out Of LIME: A Comparative Analysis Of Interpretable Machine Learning Methods*

*A Study of Earthquake Seasonality in Japan Through Network Analysis*

*Predicting Changes in the U.S. Treasury Futures Spread During the Roll Period*

*Small Fish in a Big Pond: Using Data to predict the success of Swimmers in College*

*A Stochastic Optimization Model for Managing Energy Storage Using a Driverless Fleet of Electric Vehicles*

*Using Machine Learning Methods to Predict Implied Volatility Surfaces for SPX Options*

*Deep Learning Methods and Methods in Drosophila Melangaster Classification and Pose Estimation*

*Improving Disease Progression Models With Clinical Notes*

*Modeling Opinion Dynamics as a Segmented Mean Field Game*

*Modeling the French Capital Distribution Curve with a Poisson Dirichlet Process*

*Overcoming Barriers to 100% Renewable Energy: Network Flow Optimization of California's Energy Transmission Grid*

*Identifying Network Influencers In Social Media: A Statistical Approach*

*Deep Learning Applications in Multidimensional Cash Flow Forecasting*

*Energy Risk Management: Stochastic Optimization for Industrial Gas Operations*

*A Mean Field Game Model of Credit Derivatives Markets*

*Equity Return Prediction with Augmented Regression and Factor Models*

*Counting Stars: A Pipeline for Amazon Consumer and Product Analytics with Case Studies in Discretionary Products*

*How to Succeed in Basketball Without Really Trying: A support vector machine approach to draft picks and trade deals*

*Options Pricing Using Neural Network Models and Variations on Volatility*

## Class of 2018 Post Graduate Plans

Company	Position/Type of Work
ACI Worldwide	Business Development
Alphataraxia	Data & Analytics
Alpine Investors	Data & Analytics
Anchorage Capital Group	Data & Analytics
Applied Predictive Technologies	Consulting
Bain & Company	Consulting
(5) Barclay's	Finance
(2) BlackRock	Finance
Capital One	Data & Analytics
Citadel LLC	Finance
Credit Suisse	Analyst
D. E. Shaw & Co.	Business Development
Flutterwave	Management
GCA Advisors, LLC	Finance
(4) Goldman Sachs	Finance
Guardian Life Insurance Company	Finance
Hebrew University of Jerusalem	Research
(2) IBM	Consulting
(3) JP Morgan Chase & Co.	Finance
Massachusetts Institute of Technology	PhD Operations Research
Massachusetts Institute of Technology	PhD Computer Science
(3) McKinsey & Company	Consulting



<b>Microsoft</b>	Product Management
<b>(3) Morgan Stanley</b>	Finance
<b>National Basketball Association</b>	Data & Analytics
<b>Oliver Wyman</b>	Consulting
<b>Optiver</b>	Finance
<b>Ospraie</b>	Finance
<b>Oxford</b>	Masters Computer Science
<b>PGIM The Global Investment Management Business of Prudential Financial</b>	Finance
<b>(2) Strategy&amp;</b>	Consultant
<b>Susquehanna International Group, LLP (SIG)</b>	Finance
<b>University of Pennsylvania</b>	PhD Operations Information & Decision
<b>Walmart</b>	Operations
<b>Wellington Management Company</b>	Data & Analytics
<b>Y-Strategies</b>	Finance