AERONAUTICS AND ASTRONAUTICS

Courses offered by the Department of Aeronautics and Astronautics are listed under the subject code AA on the (https://explorecourses.stanford.edu/search/?filter-term-Autumn=on&filter-catalognumber-AA=on&filter-term-Summer=on&page=0&q=AA&filter-coursestatus-Active=on&view=catalog&filter-term-Spring=on&collapse=&filter-term-Winter=on&catalog=71)*Stanford Bulletin's* ExploreCourses web site.

The Department of Aeronautics and Astronautics prepares students for professional positions in industry, government, and academia by offering a comprehensive program of undergraduate and graduate teaching and research. In this broad program, students have the opportunity to learn and integrate multiple engineering disciplines. The program emphasizes structural, aerodynamic, guidance and control, and propulsion problems of aircraft and spacecraft. Courses in the teaching program lead to the degrees of Bachelor of Science, Master of Science, Engineer, and Doctor of Philosophy. Undergraduates and doctoral students in other departments may also elect a minor in Aeronautics and Astronautics.

Requirements for all degrees include courses on basic topics in Aeronautics and Astronautics, as well as in mathematics, and related fields in engineering and the sciences.

The current research and teaching activities cover a number of advanced fields, with emphasis on:

- Aeroelasticity and Flow Simulation
- Aircraft Design, Performance, and Control
- Applied Aerodynamics
- Astrodynamics
- Autonomy
- Computational Aero-Acoustics
- Computational Fluid Dynamics
- Computational Mechanics and Dynamical Systems
- Control of Robots, including Space and Deep-Underwater Robots
- Conventional and Composite Materials and Structures
- Decision Making under Uncertainty
- Direct and Large-Eddy Simulation of Turbulence
- High-Lift Aerodynamics
- Hybrid Propulsion
- Hypersonic and Supersonic Flow
- Micro and Nano Systems and Materials
- Mission Planning and Spacecraft Operations
- Multidisciplinary Design Optimization
- Navigation Systems (especially GPS)
- Optimal Control, Estimation, System Identification
- Sensors for Harsh Environments
- Space Debris Characterization
- Space Environment Effects on Spacecraft
- Space Plasmas
- Space Policy and Economics
- Spacecraft Design and Satellite Engineering
- Spacecraft Guidance, Navigation, and Control
- Turbulent Flow and Combustion

Learning Outcomes (Undergraduate)

The department expects undergraduate majors in the program to be able to demonstrate the following learning outcomes. These learning outcomes are used in evaluating students and the department's undergraduate program. Students are expected to demonstrate:

1. an ability to apply the knowledge of mathematics, science, and engineering to understand and solve complex interdisciplinary problems.
2. an ability to design and conduct relevant experiments, as well as to analyze and interpret the resulting outcomes to make appropriate design choices.
3. the broad education necessary to understand the impact of engineering solutions in a global and societal context.
4. an ability to work professionally in aircraft and spacecraft engineering, space exploration, air- and space-based telecommunication industries, autonomous systems, robotics, commercial space transportation, teaching, research, military service, and many related technology-intensive fields.
5. an ability to understand multidisciplinary challenges of modern aircraft and spacecraft design at the system level.
6. an ability to communicate effectively and to work in diverse and inter-disciplinary teams to accomplish objectives.
7. an understanding of professional and ethical responsibility.
8. an understanding of the impact that engineering solutions can have through entrepreneurial processes.
9. a recognition of the need for and an ability to engage in life-long learning, and to make original contributions in Aeronautics and Astronautics and related fields.

Learning Outcomes (Graduate)

The purpose of the master's program is to provide students with the knowledge and skills necessary for a professional career or doctoral studies. This is done through course work which provides a solid grounding in the basic disciplines, including fluid mechanics, dynamics and control, propulsion, structural mechanics, and applied or computational mathematics, and course work or supervised research which provides depth and breadth in the student's area of specialization.

The Ph.D. is conferred upon candidates who have demonstrated substantial scholarship and the ability to conduct independent research. Through course work and guided research, the program prepares students to make original contributions in Aeronautics and Astronautics and related fields.

Graduate Programs in Aeronautics and Astronautics
Admission

To be eligible to apply for admission to the department, a student must have a bachelor's degree in engineering, physical science, mathematics, or an acceptable equivalent. Beginning with the application term 2021-2022, an MS degree will no longer be required to apply to the PhD program in Aeronautics and Astronautics. Students with a Bachelor's degree who ultimately intend to complete a PhD degree are strongly encouraged to apply directly to the PhD program, rather than the MS program. A completed application (including letters of recommendation, transcripts and GRE/TOEFL scores) must be received by the application deadline.

Information about admission to the Honors Cooperative Program is included in the "School of Engineering (http://exploredegrees.stanford.edu/schoolofengineering/#honorscooptext)" section of this bulletin. The department considers HCP applications for

the Autumn, Winter and Spring Quarters; prospective applicants may contact the department's student services office with questions.

The Graduate Record Exam (GRE) General Test is required for application to the department. Further information and application forms for all graduate degree programs may be obtained from Graduate Admissions, the Registrar's Office, http://gradadmissions.stanford.edu.

Transfer Credits

The number of transfer credits allowed for each degree (Engineer and Ph.D.) is delineated in the "Graduate Degrees (http://exploredegrees.stanford.edu/transferwork/)" section of this bulletin; transfer credit is not accepted for the master's degree. Transfer credit is allowed only for courses taken as a graduate student, after receiving a bachelor's degree, in which equivalence to Stanford courses is established and for which a grade of 'B' or better has been awarded. Transfer credits, if approved, reduce the total number of Stanford units required for a degree.

Fellowships and Assistantships

Fellowships and course or research assistantships are available to qualified graduate students. Fellowships sponsored by Gift Funds, Stanford University, and Industrial Affiliates of Stanford University in Aeronautics and Astronautics provide grants to several first-year students for up to five quarters to cover tuition and living expenses. Stanford Graduate Fellowships, sponsored by the University, provide grants for up to three full years of study and research; each year, the department is invited to nominate several outstanding doctoral or predoctoral students for these prestigious awards. Students who have excelled in their course work at Stanford are eligible for course assistantships in the department; those who have demonstrated research capability are eligible for research assistantships from individual faculty members. Students may also hold assistantships in other departments if the work is related to their academic progress; the criteria for selecting course or research assistants are determined by each hiring department. A standard, 20 hours/week course or research assistantship provides a semi-monthly salary and an 8-10 unit tuition grant per quarter. Research assistants may be given the opportunity of additional summer employment. They may use their work as the basis for a dissertation or Engineer's thesis.

Aeronautics and Astronautics Facilities

The work of the department is centered in the William F. Durand Building for Space Engineering and Science. This 120,000 square foot building houses advanced research and teaching facilities and concentrates in one complex the Department of Aeronautics and Astronautics. The Durand Building also houses faculty and staff offices and conference rooms.

Through the department's close relations with nearby NASA-Ames Research Center, students and faculty have access to one of the best and most extensive collections of experimental aeronautical research facilities in the world, as well as the latest generation of supercomputers.

General Information

Further information about the facilities and programs of the department is available at http://aa.stanford.edu, or from the department's student services office.

The department has a student branch of the American Institute of Aeronautics and Astronautics, which sponsors programs and speakers covering aerospace topics and social events. It also conducts visits to nearby research, government, and industrial facilities, and sponsors a Young Astronauts Program in the local schools.

Aeronautics and Astronautics (AA)

Mission of the Undergraduate Program in Aeronautics and Astronautics

The mission of the undergraduate program in Aeronautics and Astronautics Engineering is to provide students with the fundamental principles and techniques necessary for success and leadership in the conception, design, implementation, and operation of aerospace and related engineering systems. Courses in the major introduce students to engineering principles. Students learn to apply this fundamental knowledge to conduct laboratory experiments, and aerospace system design problems. Courses in the major include engineering fundamentals, mathematics, and the sciences, as well as in-depth courses in aeronautics and astronautics, dynamics, mechanics of materials, autonomous systems, computational engineering, embedded programming, fluids engineering, and heat transfer. The major prepares students for careers in aircraft and spacecraft engineering, autonomy, robotics, unmanned aerial vehicles, drones, space exploration, air and space-based telecommunication industries, computational engineering, teaching, research, military service, and other related technology-intensive fields.

Completion of the undergraduate program in Aeronautics and Astronautics leads to the conferral of the Bachelor of Science in Aeronautics and Astronautics.

Requirements

		Units
Mathematics		
24 units minimum		
MATH 19	Calculus (required)[1]	3
MATH 20	Calculus (required)[1]	3
MATH 21	Calculus (required)[1]	4
CME 100/ENGR 154	Vector Calculus for Engineers (required)[2]	5
or MATH 51	Linear Algebra, Multivariable Calculus, and Modern Applications	
CME 102/ENGR 155A	Ordinary Differential Equations for Engineers (required)[2]	5
or MATH 53	Ordinary Differential Equations with Linear Algebra	
CME 106/ENGR 155C	Introduction to Probability and Statistics for Engineers (required)	4-5
or STATS 110	Statistical Methods in Engineering and the Physical Sciences	
or STATS 116	Theory of Probability	
or CS 109	Introduction to Probability for Computer Scientists	
CME 104	Linear Algebra and Partial Differential Equations for Engineers (recommended)[2]	5
or MATH 52	Integral Calculus of Several Variables	
CME 108	Introduction to Scientific Computing (recommended)	3
Science		
20 units minimum		
PHYSICS 41	Mechanics (required)[3]	4
or PHYSICS 41E	Mechanics, Concepts, Calculations, and Context	
PHYSICS 43	Electricity and Magnetism (required)[3]	4
PHYSICS 45	Light and Heat (required)	4
CHEM 31M	Chemical Principles: From Molecules to Solids (or CHEM 31A and CHEM 31B, or AP Chemistry) (required)	5
ENGR 80	Introduction to Bioengineering (Engineering Living Matter) (recommended)	4

School of Engineering approved Science Electives: See Undergraduate Handbook, Figure 4-2		3-5
Technology in Society (one course required)		
School of Engineering approved Technology in Society courses: See Undergraduate Handbook, Figure 4-3. The course must be on the School of Engineering approved list the year you take it.		3-5
AA 252	Techniques of Failure Analysis (recommended)	3
Engineering Fundamentals (three courses required)		
11 units minimum		
ENGR 21	Engineering of Systems (required)	3
CS 106A	Programming Methodology	3-5
ENGR 10	Introduction to Engineering Analysis (recommended)	4
ENGR 40M	An Intro to Making: What is EE (recommended)	3-5
Fundamentals Elective; see list of Approved Courses in Undergraduate Engineering Handbook website at ughb.stanford.edu, Figure 4-4		3-5
Aero/Astro Depth Requirements		
35 units minimum		
ENGR 14	Intro to Solid Mechanics (required)	3
ENGR 15	Dynamics (required)	3
ENGR 105	Feedback Control Design (required)	3
ME 30	Engineering Thermodynamics (required)	3
ME 70	Introductory Fluids Engineering (required)	3
AA 100	Introduction to Aeronautics and Astronautics (required)	3
AA 131	Space Flight (required)	3
AA 141	Atmospheric Flight (required)	3
AA 151	Lightweight Structures (required)	3
AA 174A	Principles of Robot Autonomy I (required)	5
AA 190	Directed Research and Writing in Aero/Astro (required) satisfies the Writing in the Major requirement, (WIM)	3-5
Aero/Astro Focus Electives		
12 units minimum		
AA 102	Introduction to Applied Aerodynamics (recommended)	3
AA 103	Air and Space Propulsion	3
AA 113	Aerospace Computational Science	3
AA 135	Introduction to Space Policy	3
AA 156	Mechanics of Composite Materials	3
AA 173	Flight Mechanics & Controls	3
CS 237B	Principles of Robot Autonomy II (AA 174B)	3-4
AA 199	Independent Study in Aero/Astro	1-5
AA 261	Building an Aerospace Startup from the Ground Up	3
AA 272	Global Positioning Systems	3
AA 279A	Space Mechanics	3
MS&E 178	The Spirit of Entrepreneurship	2
Aero/Astro Suggested Courses (not required)		
AA 149	Operation of Aerospace Systems	1
Aero/Astro Capstone Requirement		
7 units minimum. Select either the Spacecraft or Aircraft course sequence		
AA 136A	Spacecraft Design	3-5
AA 136B	Spacecraft Design Laboratory	3-5
AA 146A	Aircraft Design	4
AA 146B	Aircraft Design Laboratory	3

For additional information and sample programs see the Handbook for Undergraduate Engineering (http://ughb.stanford.edu) and the Aeronautics and Astronautics Undergraduate Program Sheet (https://ughb.stanford.edu/program-sheets/).

All courses taken for the major must be taken for a letter grade if that option is offered by the instructor.

Minimum Combined GPA for all courses in Engineering Topics (Engineering Fundamentals and Depth courses) is 2.0.

Transfer and AP credits in Math, Science, Fundamentals, and the Technology in Society course must be approved by the School of Engineering Dean's office.

[1] A score of 4 on the Calculus BC test or 5 on the AB test only gives students 8 units, not 10 units, so is equal to MATH 19 + MATH 20, but not MATH 21. The Math Placement Exam determines what math course the student starts with.

[2] It is recommended that the CME series (100, 102, 104) be taken rather than the MATH series (51, 52, 53). It is recommended that students taking the MATH series also take CME 192 Introduction to MATLAB.

[3] A score of 5 on the AP Physics C Mechanics test places the student out of PHYSICS 41. Similarly, a score of 5 on the AP Physics Electricity and Magnetism test places the student out of PHYSICS 43.

Honors Program

The Department of Aeronautics and Astronautics honors program has been designed to allow undergraduates with strong records and enthusiasm for independent research to engage in a significant project leading to a degree with departmental honors.

Students who meet the eligibility criteria and wish to be considered for the honors program should apply to the program by the end of the junior year. All applications are subject to the review and final approval by the Aero/Astro Undergraduate Curriculum Committee.

Application Requirements:

- One-page written statement describing the research topic and signed adviser form
- GPA of 3.5 or higher in the major
- Unofficial Stanford transcript (from Axess)
- Signature of thesis adviser

Honors criteria:

- Maintain the 3.5 GPA required for admissions to the honors program.
- Arrangement with an Aero/Astro faculty member who agrees to serve as the thesis adviser. The adviser must be a member of the Academic Council.
- Under the direction of the thesis adviser, complete at least two quarters of research with a minimum of 9 units of independent research; 3 of these units may be used towards a student's Aero/Astro Focus Elective requirement.
- Submit an honors thesis (20-30 pages). Thesis is due by April 30th of senior year in order to be eligible for University prizes.
- Attend Research Experience for Undergraduates Poster Session or present in another suitable forum approved by the faculty adviser.

Aeronautics and Astronautics (AA) Minor

The Aero/Astro minor introduces undergraduates to the key elements of modern aerospace systems. Within the minor, students may focus

on aircraft, spacecraft, or disciplines relevant to both. The course requirements for the minor are described in detail below. If any core classes (aside from ENGR 21; see footnote) are part of student's major or other degree program, the Aero/Astro adviser can help select substitute courses to fulfill the Aero/Astro minor requirements; no double counting allowed. All courses taken for the minor must be taken for a letter grade if that option is offered by the instructor. Minimum GPA for all minor courses combined is 2.0.

The following core courses fulfill the minor requirements:

		Units
AA Core		
12 Core Units, 24 Total Program Units		
ENGR 21	Engineering of Systems [1]	3
AA 100	Introduction to Aeronautics and Astronautics	3
AA 131	Space Flight	3
AA 141	Atmospheric Flight	3
AA Electives		
Choose 4 courses		
ENGR 105	Feedback Control Design	3
ME 70	Introductory Fluids Engineering	3
AA 102	Introduction to Applied Aerodynamics	3
AA 103	Air and Space Propulsion	3
AA 135	Introduction to Space Policy	3
AA 151	Lightweight Structures	3
AA 156	Mechanics of Composite Materials	3
AA 173	Flight Mechanics & Controls	3
AA 174A	Principles of Robot Autonomy I	3-4
CS 237B	Principles of Robot Autonomy II	3-4
AA 261	Building an Aerospace Startup from the Ground Up	3
AA 272	Global Positioning Systems	3
AA 279A	Space Mechanics	3

[1]   ENGR 21 is waived as minor requirement if already taken as part of the major program.

Master of Science in Aeronautics and Astronautics

The University's basic requirements for the master's degree are outlined in the "Graduate Degrees (http://exploredegrees.stanford.edu/graduatedegrees/)" section of this bulletin.

Students with an aeronautical engineering background should be able to complete the master's degree in five quarters; note that many courses are not taught during the summer. Students with a bachelor's degree in Physical Science, Mathematics, or other areas of Engineering may find it necessary to take certain prerequisite courses, which may lengthen the time required to obtain the master's degree.

The Master of Science (M.S.) program is a terminal degree program. It is based on the completion of lecture courses focused on a theme within the discipline of Aeronautics and Astronautics engineering. No thesis is offered. Research is optional (required to take the qualifying examination).

Grade Point Averages

A minimum grade point average (GPA) of 2.75 is required to fulfill the department's master's degree requirements. A minimum GPA of 3.5 is required for eligibility to attempt the Ph.D. qualifying examination. Students must also meet the University's quarterly academic

requirements for graduate students as described in the "Degree Progress (http://exploredegrees.stanford.edu/graduatedegrees/#degreeprogresstext)" section of this bulletin and in the "Satisfactory Progress" section of the Guide to Graduate Studies in Aeronautics and Astronautics. All courses (excluding seminars) used to satisfy the requirements for basic courses, mathematics and technical electives must be taken for a letter grade. Insufficient grade points on which to base the GPA may delay expected degree conferral or result in refusal of permission to take the qualifying examinations.

Course Requirements

The master's degree program requires 45 quarter units of course work, which must be taken at Stanford. The course work is divided into four categories:

- Basic Courses
- Mathematics Courses
- Technical Electives
- Other Electives

Basic Courses

Master's degree candidates must select eight courses as follows:

		Units
(I) Five courses in the basic areas of Aeronautics and Astronautics (one in each area):		
Fluids		
AA 200	Applied Aerodynamics	3
AA 210A	Fundamentals of Compressible Flow	3
Structures		
AA 240	Analysis of Structures	3
Guidance and Control		
ENGR 105	Feedback Control Design	3
ENGR 205	Introduction to Control Design Techniques	3
Propulsion		
AA 283	Aircraft and Rocket Propulsion	3
Experimentation/Design Requirements (see courses under Related Courses tab above)		
(II) Three courses (one each from three of the four areas below)		
Fluids		
AA 200	Applied Aerodynamics	3
AA 210A	Fundamentals of Compressible Flow	3
AA 244A	Introduction to Plasma Physics and Engineering	3
Structures		
AA 242B	Mechanical Vibrations	3
AA 256	Mechanics of Composites	3
AA 280	Smart Structures	3
Guidance and Control		
AA 242A	Classical Dynamics	3
AA 242B	Mechanical Vibrations	3
AA 251	Introduction to the Space Environment	3
AA 271A	Dynamics and Control of Aircraft	3
AA 272	Global Positioning Systems	3
AA 274A	Principles of Robot Autonomy I	3-4
AA 277	Multi-Robot Control and Distributed Optimization	3
AA 279A	Space Mechanics	3

One course selected from AA courses numbered 200 and above, excluding seminars and independent research

Course Waivers

Waivers of the basic courses required for the M.S. degree in Aeronautics and Astronautics can only be granted by the instructor of that course. Students who believe that they have had a substantially equivalent course at another institution should consult with the course instructor to determine if they are eligible for a waiver, and with their adviser to judge the effect on their overall program plans. To request a waiver, students should fill out a Petition for Waiver form (reverse side of the department's program proposal) and have it approved by the instructor and their adviser. One additional technical elective must be added for each basic course that is waived.

Mathematics Courses

M.S. candidates are expected to exhibit competence in applied mathematics. Students meet this requirement by taking two courses, for a minimum of 6 units, of either advanced mathematics offered by the Mathematics Department or technical electives that strongly emphasize applied mathematics. Common choices include:

- AA 203 Optimal and Learning-based Control
- AA 212 Advanced Feedback Control Design
- AA 214 Numerical Methods for Compressible Flows

- AA 218 Introduction to Symmetry Analysis
- AA 222 Engineering Design Optimization
- AA 228 Decision Making under Uncertainty
- AA 242B Mechanical Vibrations

See the list of mathematics courses under Related Courses (http://exploredegrees.stanford.edu/aeronauticsandastronautics/#relatedcoursestext) tab for additional suggestions, which includes all courses in the Mathematics Department numbered 200 or above.

A maximum of three independent study/research units (AA 290 or independent study in another department) may count toward your M.S. program. If you fulfill your experimentation/design requirement with a course other than AA 290 (or equivalent from another department), it is possible to count AA 290 as a technical or free elective.

Technical Electives

Students, in consultation with their adviser, select at least four courses* from among the graduate-level courses, totaling at least 12 units, from departments in the School of Engineering and related science departments. These courses should be taken for a letter grade; the student should not elect the credit/no-credit option for any course except free elective.

*Up to three seminar units may count toward an M.S. program, and are counted as one technical elective. At least three additional graduate courses offered in Engineering or related math/science departments should be taken to meet the technical elective section requirement.

Other Electives

It is recommended that all candidates enroll in a humanities or social sciences course to complete the 45-unit requirement. Practicing courses in, for example, art, music, and physical education do not qualify in this category. Language courses may qualify.

Coterminal Master's Program in Aeronautics and Astronautics

This program allows Stanford undergraduates an opportunity to work simultaneously toward a B.S. degree and an M.S. in Aeronautics and Astronautics. Stanford undergraduates who wish to continue their studies for the master of science degree in the coterminal program must have earned a minimum of 120 units towards graduation. This includes allowable Advanced Placement (AP) and transfer credit.

The department-specific Aero/Astro coterminal program application, which includes information and deadlines, can be obtained from the Aero/Astro Student Services Office (https://aa.stanford.edu/academics/student-services-office/). A completed application (including letters of recommendation, transcripts and GRE scores) must be received no later than the quarter prior to the expected completion of the undergraduate degree. Admission is granted or denied through the departmental faculty admissions committee. Stanford undergraduates interested in learning more about receiving an Aero/Astro master's degree as a coterm student should review the information on the University Registrar's web site (https://registrar.stanford.edu/students/coterminal-degree-programs/) and visit the Aero/Astro Student Services Office (https://aa.stanford.edu/academics/student-services-office/).

University Coterminal Requirements

Coterminal master's degree candidates are expected to complete all master's degree requirements as described in this bulletin. University requirements for the coterminal master's degree are described in the "Coterminal Master's Program (http://exploredegrees.stanford.edu/cotermdegrees/)" section. University requirements for the master's degree are described in the "Graduate Degrees (http://exploredegrees.stanford.edu/graduatedegrees/#masterstext)" section of this bulletin.

After accepting admission to this coterminal master's degree program, students may request transfer of courses from the undergraduate to the graduate career to satisfy requirements for the master's degree. Transfer of courses to the graduate career requires review and approval of both the undergraduate and graduate programs on a case by case basis.

In this master's program, courses taken during or after the first quarter of the sophomore year are eligible for consideration for transfer to the graduate career; the timing of the first graduate quarter is not a factor. No courses taken prior to the first quarter of the sophomore year may be used to meet master's degree requirements.

Course transfers are not possible after the bachelor's degree has been conferred.

The University requires that the graduate advisor be assigned in the student's first graduate quarter even though the undergraduate career may still be open. The University also requires that the Master's Degree Program Proposal be completed by the student and approved by the department by the end of the student's first graduate quarter.

The Honors Cooperative Program

The Honors Cooperative Program (HCP) makes it possible for academically qualified engineers and scientists in nearby companies to be part-time master's students in Aeronautics and Astronautics while continuing nearly full-time professional employment. Prospective HCP students follow the same admission process and must meet the same admission requirements as full-time master's students. For more information regarding the Honors Cooperative Program, see the "School of Engineering (http://exploredegrees.stanford.edu/schoolofengineering/#honorscooptext)" section of this bulletin.

Master of Science in Engineering (AA)

Students whose career objectives require a more interdepartmental or narrowly focused program than is possible in the M.S. program in Aeronautics and Astronautics (Aero/Astro) may pursue a program for an M.S. degree in Engineering (45 units). This program is described in the "Graduate Programs in the School of Engineering (http://exploredegrees.stanford.edu/schoolofengineering/#masters)" section of this bulletin.

Sponsorship by the Department of Aeronautics and Astronautics in this more general program requires that the student file a proposal before completing 18 units of the proposed graduate program. The proposal

must be accompanied by a statement explaining the objectives of the program and how the program is coherent, contains depth, and fulfills a well-defined career objective. The proposed program must include at least 12 units of graduate-level work in the department and meet rigorous standards of technical breadth and depth comparable to the regular Aero/ Astro Master of Science program. The grade and unit requirements are the same as for the M.S. degree in Aeronautics and Astronautics.

Engineer in Aeronautics and Astronautics

The degree of Engineer represents an additional year (or more) of study beyond the M.S. degree and includes a research thesis. The program is designed for students who wish to do professional engineering work upon graduation and who want to engage in more specialized study than is afforded by the master's degree alone. It is expected that full-time students will be able to complete the degree within two years of study after the master's degree.

The University's basic requirements for the degree of Engineer are outlined in the "Graduate Degrees (http://exploredegrees.stanford.edu/graduatedegrees/)" section of this bulletin. The following are department requirements.

The candidate's prior study program should have fulfilled the department's requirements for the master's degree or a substantial equivalent. Beyond the master's degree, a total of 45 units of work is required, including a thesis and a minimum of 21 units of courses chosen as follows:

1. 21 units of approved technical electives, of which 6 are in mathematics or applied mathematics. See the list of mathematics courses under Related Courses tab above. All courses in the Mathematics Department numbered 200 or above are included. The remaining 15 units are chosen in consultation with the adviser, and represent a coherent field of study related to the thesis topic. Suggested fields include: (a) acoustics, (b) aerospace structures, (c) aerospace systems synthesis and design, (d) analytical and experimental methods in solid and fluid mechanics, (e) computational fluid dynamics, and (f) guidance and control.
2. The remaining 24 units may be thesis, research, technical courses, or free electives.

Candidates for the degree of Engineer are expected to have a minimum grade point average (GPA) of 3.0 for work in courses beyond those required for the master's degree. All courses except seminars and directed research should be taken for a letter grade.

Engineer's thesis

For specific information on the format and deadlines for submission of theses, please check with the Graduate Degree Progress Office. The department recommends that students follow the format defined in the handbook Directions for Preparing Doctoral Dissertations (https://studentaffairs.stanford.edu/registrar/students/dissertation-thesis/), available in the Graduate Degree Progress Office. Note: the adviser must sign the thesis before the filing deadline, which is generally the last day of classes during the graduation quarter.

Doctor of Philosophy in Aeronautics and Astronautics

The University's basic requirements for the Ph.D. degree are outlined in the "Graduate Degrees (http://exploredegrees.stanford.edu/graduatedegrees/)" section of this bulletin.

Department requirements are stated below. Beginning with the application term 2021-22, an M.S. degree is no longer required to apply to the Ph.D. program in Aeronautics and Astronautics. Students with a bachelor's degree who ultimately intend to complete a Ph.D. degree are strongly encouraged to apply directly to the Ph.D. program, rather than the M.S. program. Students who are currently pursuing the M.S. in the department and wish to continue for the Ph.D. should submit a graduate program authorization petition form online through Axess before their last quarter in the master's program.

Before beginning dissertation research for the Ph.D. degree, a student must pass the departmental qualifying examination. A student must meet the following conditions by the appropriate deadline to be able to take the qualifying examination:

1. 30 units of master's course work completed. A student who has completed fewer than 30 units may petition to take the qualifying examination.
2. Stanford graduate GPA of 3.5 or higher.
3. Investigation of a research problem, under the direction of a faculty member who evaluates this work as evidence of the potential for doctoral research. The minimum requirement for taking the qualifying examination is to complete 3 units of AA 290 before the qualifying examination quarter.

Additional information about the deadlines, nature, and scope of the Ph.D. qualifying examination can be obtained from the department. Recommended courses to prepare for the qualifying examination are listed on the Aero/Astro website (http://aa.stanford.edu/academics/graduate-programs/doctoral-program/). After passing the exam, the student must submit an approved program of Ph.D. course work on an Application for Candidacy for Doctoral Degree to the Aero/Astro student services office.

Course Requirements

Each individual Ph.D. program in Aeronautics and Astronautics, designed by the student in consultation with the adviser, should represent a strong and cohesive program reflecting the student's major field of interest. A total of 90 units of credit is required beyond the M.S. Of these 90 units, a minimum of 27 must be formal course work (excluding research, directed study and seminars), consisting primarily of graduate courses in engineering and the pertinent sciences. The remainder of the 90 units may be in the form of either Ph.D. dissertation units or free electives. For students who elect a minor in another department, a maximum of 9 units from the minor program may be included in the 27 units of formal course work; the remaining minor units may be considered free electives and are included in the 90 unit total required for the Aero/Astro Ph.D. degree.

Ph.D. students in Aeronautics and Astronautics must take 9 units of mathematics courses, with at least 6 of these units from courses with numbers over 200. The Aero/Astro department and other engineering departments offer many courses that have sufficient mathematical content that they may be used to satisfy the mathematics requirement. See the list of mathematics courses under Related Courses (p. 8) tab for suggestions. Others may be acceptable if approved by the adviser and the Aero/Astro student services office. University requirements for continuous registration apply to doctoral students for the duration of the degree.

Grade Point Average

A minimum grade point average (GPA) of 3.0 is required to fulfill the department's Ph.D. degree requirements. It is incumbent upon Ph.D. students to request letter grades in all courses listed on the Application for Candidacy form.

Candidacy

Ph.D. students must complete the candidacy process and be admitted to candidacy by their second year of doctoral study. There are two requirements for admission to Ph.D. candidacy in Aeronautics and Astronautics: students must first pass the departmental qualifying exam and must then submit an application for candidacy. The candidacy form

lists the courses the student will take to fulfill the requirements for the degree. The form must include the 90 non-M.S. units required for the Ph.D.; it should be signed by the adviser and submitted to the Aero/Astro student services office for the candidacy chairman's signature. Aero/Astro has a department-specific candidacy form, which may be obtained in the Aero/Astro student services office. Candidacy is valid for up to five years; this term is not affected by leaves of absence.

Dissertation Reading Committee

Each Ph.D. candidate is required to establish a reading committee for the doctoral dissertation within six months after passing the department's Ph.D. qualifying exam. Thereafter, the student should consult frequently with all members of the committee about the direction and progress of the dissertation research.

A dissertation reading committee consists of the principal dissertation adviser and at least two other readers. If the principal adviser is emeritus, there should be a non-emeritus co-adviser. It is expected that at least two members of the Aero/Astro faculty be on each reading committee. If the principal research adviser is not within the Aero/Astro department, then the student's Aero/Astro academic adviser should be one of those members. The initial committee, and any subsequent changes, must be approved by the department Chair.

Although all readers are usually members of the Stanford Academic Council, the department Chair may approve one non-Academic Council reader if the person brings unusual and necessary expertise to the dissertation research. Generally, this non-Academic Council reader will be a fourth reader, in addition to three Academic Council members.

University Oral Examination

The Ph.D. candidate is required to take the University oral examination after the dissertation is substantially completed (with the dissertation draft in writing), but before final approval. The examination consists of a public presentation of dissertation research, followed by substantive private questioning on the dissertation and related fields by the University oral committee (four faculty examiners, plus a chairman). The examiners usually include the three members on the student's Ph.D. reading committee. The chairman must not be in the same department as the student or the adviser. Once the oral examination has been passed, the student finalizes the dissertation for reading committee review and final approval. Forms for the University oral examination scheduling and a one-page dissertation abstract should be submitted to the Aero/Astro student services office at least three weeks prior to the date of the oral examination for departmental review and approval. Students must be enrolled during the quarter when they take their University oral examination. If the oral examination takes place during the vacation time between quarters, the student must be enrolled in the prior quarter.

Doctoral Dissertation

See the Directions for Preparing Doctoral Dissertation (https://registrar.stanford.edu/students/dissertation-and-thesis-submission/preparing-dissertations-electronic-submission/format/), which outlines the University guidelines for preparing a Ph.D. dissertation.

When a student is ready for a final draft of the dissertation, the student should make an appointment to consult with the graduate degree progress officer in the Registrar's Office to review the completion of the Ph.D. program and the strict formatting requirements for the dissertation. Students must submit the final version of the dissertation to the Registrar's Office no later than the posted deadline. *Note:* All members of the reading committee must sign the dissertation before the filing deadline.

The student's Ph.D. reading committee and University oral committee must each include at least one faculty member from Aeronautics and Astronautics.

Ph.D. Minor in Aeronautics and Astronautics

A student who wishes to obtain a Ph.D. minor in Aeronautics and Astronautics should consult the Aero/Astro student services office for designation of a minor adviser. A minor in Aeronautics and Astronautics may be obtained by completing 20 units of graduate-level courses in the Department of Aeronautics and Astronautics, following a program and performance approved by the department's candidacy chair. The student's Ph.D. reading committee and University oral committee must each include at least one faculty member from Aero/Astro.

COVID-19 Policies

On July 30, the Academic Senate adopted grading policies effective for all undergraduate and graduate programs, excepting the professional Graduate School of Business, School of Law, and the School of Medicine M.D. Program. For a complete list of those and other academic policies relating to the pandemic, see the "COVID-19 and Academic Continuity (http://exploredegrees.stanford.edu/covid-19-policy-changes/#tempdepttemplatetabtext)" section of this bulletin.

The Senate decided that all undergraduate and graduate courses offered for a letter grade must also offer students the option of taking the course for a "credit" or "no credit" grade and recommended that deans, departments, and programs consider adopting local policies to count courses taken for a "credit" or "satisfactory" grade toward the fulfillment of degree-program requirements and/or alter program requirements as appropriate.

Undergraduate Degree Requirements
Grading

While students are encouraged to take courses for a letter grade whenever possible, the Aeronautics and Astronautics Department counts all courses taken in academic year 2020-21 with a grade of 'CR' (credit) or 'S' (satisfactory) towards satisfaction of undergraduate degree requirements that otherwise require a letter grade.

Graduate Degree Requirements
Grading

The Aeronautics and Astronautics Department has not changed its policy concerning utilization of 'CR' (credit) or 'S' (satisfactory) grades towards degree requirements requiring a letter grade for academic year 2020-21. However, to accommodate students who have been impacted in different ways by COVID-19 during the academic year 2020-21, students may submit a petition requesting to have a course with a grade of 'CR' (credit) or 'S' (satisfactory) count towards degree requirements that otherwise require a letter grade. Any petition submitted after the Change of Grading Basis Deadline will require additional approval by the Registrar's Office.

Graduate Advising Expectations

The Department of Aeronautics and Astronautics is committed to providing academic advising in support of graduate student education and professional development. The advising relationship should entail collaborative engagement by both the adviser and the advisee. As a best practice, advising expectations should be discussed and reviewed to ensure mutual understanding. Both the adviser and the advisee are expected to maintain professionalism and integrity.

Graduate students are active contributors to the advising relationship, proactively seeking academic and professional guidance and taking responsibility for informing themselves of policies and degree requirements for their graduate program.

In addition, the faculty Candidacy Chair is available for consultation during the academic year by email and during office hours. The Aero/Astro student services office is also an important part of the advising team. Staff in the office inform students and advisers about university and department requirements, procedures, and opportunities, and maintain the official records of advising assignments and approvals.

For a statement of University policy on graduate advising, see the "Graduate Advising (http://exploredegrees.stanford.edu/graduatedegrees/#advisingandcredentialstext)" section of this bulletin.

Master of Science

At the start of graduate study, each student is assigned a master's program adviser: a member of our faculty who provides guidance in course selection, course planning, and in exploring short and long term academic opportunities and professional pathways. The program adviser serves as the first resource for consultation and advice about a student's academic program. The Guide to Graduate Studies in Aeronautics and Astronautics (https://aa.stanford.edu/sites/default/files/aa_guide_to_graduate_studies_2017-18_0.pdf) provides information and suggested timelines for advising meetings. Usually, the same faculty member serves as program adviser for the duration of master's study. In rare instances, a formal adviser change request may be considered. See the Aero/Astro student services office for additional information on this process.

Ph.D. and Engineer

Faculty research advisers guide students in key areas such as selecting courses, designing and conducting research, developing of teaching pedagogy, navigating policies and degree requirements, and exploring academic opportunities and professional pathways. The Guide to Graduate Studies in Aeronautics and Astronautics (https://aa.stanford.edu/sites/default/files/aa_guide_to_graduate_studies_2017-18_0.pdf) provides information and suggested timelines for advising meetings in the different stages of the doctoral or engineering program. Each individual program, designed by the student in consultation with the research adviser, should represent a strong and cohesive program reflecting the student's major field of interest. When the research adviser is from outside the Aero/Astro department, the student must also identify a program adviser from departmental primary faculty to provide guidance on departmental requirements and opportunities.

Emeriti: (Professors) Arthur E. Bryson, Richard Christensen, Daniel B. DeBra, Antony Jameson, Robert W. MacCormack, Bradford W. Parkinson*, J. David Powell*, George S. Springer, Charles Steele, Stephen W. Tsai*

Chair: Charbel Farhat

Director of Graduate Studies: Stephen Rock

Director of Undergraduate Studies: Marco Pavone

Professors: Juan Alonso, Brian J. Cantwell, Fu-Kuo Chang, Charbel Farhat, Ilan Kroo, Sanjiva Lele, Stephen Rock

Professor (Research): Todd Walter

Associate Professor: Sigrid Close, Mykel Kochenderfer, Marco Pavone, Debbie Senesky

Assistant Professors: Simone D'Amico, Grace Gao, Ken Hara, Mac Schwager

Adjunct Professors: Andrew Barrows, G. Scott Hubbard

Lecturers: Abid Kemal, Sherman Lo

* Recalled to active duty.

Experimentation/Design Requirements Courses

The following courses satisfy the master's Experimentation/Design Requirements.

		Units
AA 236A	Spacecraft Design	4
AA 236B	Spacecraft Design Laboratory	3-5
AA 236C	Spacecraft Design Laboratory	3-5
AA 274A	Principles of Robot Autonomy I	3-5
AA 279C	Spacecraft Attitude Determination and Control	3
AA 279D	Spacecraft Formation-Flying and Rendezvous	3
AA 284B	Propulsion System Design Laboratory	3
AA 284C	Propulsion System Design Laboratory	3
CS 225A	Experimental Robotics	3
CS 402L	Beyond Bits and Atoms - Lab	1-3
EE 233	Analog Communications Design Laboratory	3-4
EE 234	Photonics Laboratory	3
EE 251	High-Frequency Circuit Design Laboratory	3
EE 312	Integrated Circuit Fabrication Laboratory	3-4
ENGR 341	Micro/Nano Systems Design and Fabrication	3-5
MATSCI 160	Nanomaterials Laboratory	3-4
MATSCI 164	Electronic and Photonic Materials and Devices Laboratory	3-4
MATSCI 171	Energy Materials Laboratory	3-4
MATSCI 172	X-Ray Diffraction Laboratory	3-4
MATSCI 173	Mechanical Behavior Laboratory	3-4
MATSCI 322	Transmission Electron Microscopy Laboratory	3
ME 210	Introduction to Mechatronics	4
ME 218A	Smart Product Design Fundamentals	4-5
ME 218B	Smart Product Design Applications	4-5
ME 218C	Smart Product Design Practice	4-5
ME 218D	Smart Product Design: Projects	3-4
ME 220	Introduction to Sensors	4
ME 310A	Global Engineering Design Thinking, Innovation, and Entrepreneurship	4
ME 310B	Global Engineering Design Thinking, Innovation, and Entrepreneurship	4
ME 310C	Global Engineering Design Thinking, Innovation, and Entrepreneurship	4
ME 324	Precision Engineering	4
ME 348	Experimental Stress Analysis	3
ME 354	Experimental Methods in Fluid Mechanics	4-5
ME 367	Optical Diagnostics and Spectroscopy Laboratory	4

Mathematics Courses

Each Aero/Astro degree has a mathematics requirement, for which courses on the following list are pre-approved. (Other advanced courses may also be acceptable.) Students should consult with their advisers in selecting the most appropriate classes for their field. M.S. candidates select 2 courses; they may also use the mathematics courses listed as common choices in the master's degree course requirements . Engineers

select 2 courses; Ph.D. candidates select 3 courses, with at least 6 units from courses numbered above 200.

		Units
AA 203	Optimal and Learning-based Control	3
AA 212	Advanced Feedback Control Design	3
AA 214	Numerical Methods for Compressible Flows	3
AA 218	Introduction to Symmetry Analysis	3
AA 222	Engineering Design Optimization	3-4
AA 228	Decision Making under Uncertainty	3-4
AA 242B	Mechanical Vibrations	3
AA 273	State Estimation and Filtering for Robotic Perception	3
AA 277	Multi-Robot Control and Distributed Optimization	3
CEE 281	Mechanics and Finite Elements	3
CME 108	Introduction to Scientific Computing	3
CME 302	Numerical Linear Algebra	3
CME 303	Partial Differential Equations of Applied Mathematics	3
CME 306	Numerical Solution of Partial Differential Equations	3
CME 307	Optimization	3
CME 308	Stochastic Methods in Engineering	3
CS 221	Artificial Intelligence: Principles and Techniques	3-4
CS 229	Machine Learning	3-4
EE 261	The Fourier Transform and Its Applications	3
EE 263	Introduction to Linear Dynamical Systems	3
EE 264	Digital Signal Processing	3-4
EE 278	Introduction to Statistical Signal Processing	3
EE 364A	Convex Optimization I	3
EE 364B	Convex Optimization II	3
ENGR 207B	Linear Control Systems II	3
ENGR 209A	Analysis and Control of Nonlinear Systems	3
MATH 113	Linear Algebra and Matrix Theory	3
MATH 115	Functions of a Real Variable	3
MATH 120	Groups and Rings	3
MATH 171	Fundamental Concepts of Analysis	3
ME 300A	Linear Algebra with Application to Engineering Computations	3
ME 300B	Partial Differential Equations in Engineering	3
ME 300C	Introduction to Numerical Methods for Engineering	3
ME 335A	Finite Element Analysis	3
ME 335B	Finite Element Analysis	3
ME 335C	Finite Element Analysis	3
ME 408	Spectral Methods in Computational Physics	3
ME 469	Computational Methods in Fluid Mechanics	3
MS&E 201	Dynamic Systems	3
MS&E 221	Stochastic Modeling	3
MS&E 311	Optimization	3
MS&E 351	Dynamic Programming and Stochastic Control	3
PHYSICS 211	Continuum Mechanics	3
STATS 110	Statistical Methods in Engineering and the Physical Sciences	5
STATS 116	Theory of Probability	4
STATS 217	Introduction to Stochastic Processes I	3

Courses

AA 47SI. Why Go To Space?. 1 Unit.
Why do we spend billions of dollars exploring space? What can modern policymakers, entrepreneurs, and industrialists do to help us achieve our goals beyond planet Earth? Whether it is the object of exploration, science, civilization, or conquest, few domains have captured the imagination of a species like space. This course is an introduction to space policy issues, with an emphasis on the modern United States. We will present a historical overview of space programs from all around the world, and then spend the last five weeks discussing present policy issues, through lectures and guest speakers from NASA, the Department of Defense, new and legacy space industry companies, and more. Students will present on one issue that piques their interest, selecting from various domains including commercial concerns, military questions, and geopolitical considerations.

AA 93. Building Trust in Autonomy. 1 Unit.
Preparatory course for Bing Overseas Studies summer course in Edinburgh. Prerequisite: Requires instructor consent.

AA 100. Introduction to Aeronautics and Astronautics. 3 Units.
This class introduces the basics of aeronautics and astronautics through applied physics, hands-on activities, and real world examples. The principles of fluid flow, flight, and propulsion for aircraft will be illustrated, including the creation of lift and drag, aerodynamic performance including takeoff, climb, range, and landing. The principles of orbits, maneuvers, space environment, and propulsion for spacecraft will be illustrated. Students will be exposed to the history and challenges of aeronautics and astronautics.

AA 102. Introduction to Applied Aerodynamics. 3 Units.
This course explores the fundamentals of the behavior of aerodynamic surfaces (airfoils, wings, bodies) immersed in a fluid across all speed regimes (from subsonic to supersonic/hypersonic). We will cover airfoil theory (subsonic and supersonic), wing theory, and introduction to viscous flows and both laminar and turbulent boundary layers, and the topic of flow transition. At the completion of this course, students will be able to understand and predict the forces and movements generated by aerodynamic configurations of interest. Assignments require a basic introductory knowledge of MATLAB or another suitable programming language. Prerequisites: CME 100 and CME 102 (or equivalent), PHYS 41, AA 100, and AA 101 or ME 70.

AA 103. Air and Space Propulsion. 3 Units.
This course is designed to introduce the student to fundamental concepts of air-breathing and rocket propulsion including advanced concepts for space propulsion. Topics: the physical mechanisms of thrust creation and the parameters used to characterize propulsion system performance; comparison of airbreathing engine cycles; introduction to chemical rockets; multistage launch systems; plasmas and electric propulsion; solar sails and laser assisted propulsion. Prerequisites: AA 100, ENGR 30, and ME 70 (or equivalent).

AA 108N. Surviving Space. 3 Units.
Space is dangerous. Anything we put into orbit has to survive the intense forces experienced during launch, extreme temperature changes, impacts by cosmic rays and energetic protons and electrons, as well as hits by human-made orbital debris and meteoroids. If we venture beyond Earth's sphere of influence, we must also then endure the extreme plasma environment without the protection of our magnetic field. With all of these potential hazards, it is remarkable that our space program has experienced so few catastrophic failures. In this seminar, students will learn how engineers design and test spacecraft to ensure survivability in this harsh space environment. We will explore three different space environment scenarios, including a small satellite that must survive in Low Earth Orbit (LEO), a large spacecraft headed to rendezvous with an asteroid, and a human spaceflight mission to Mars.

AA 109Q. Aerodynamics of Race Cars. 3 Units.
Almost as soon as cars had been invented, races of various kinds were organized. In all its forms (open-wheel, touring car, sports car, production-car, one-make, stock car, etc.), car racing is today a very popular sport with a huge media coverage and significant commercial sponsorships. More importantly, it is a proving ground for new technologies and a battlefield for the giants of the automotive industry. While race car performance depends on elements such as engine power, chassis design, tire adhesion and of course, the driver, aerodynamics probably plays the most vital role in determining the performance and efficiency of a race car. Front and/or rear wings are visible on many of them. During this seminar, you will learn about many other critical components of a race car including diffusers and add-ons such as vortex generators and spoilers. You will also discover that due to the competitive nature of this sport and its associated short design cycles, engineering decisions about a race car must rely on combined information from track, wind tunnel, and numerical computations. It is clear that airplanes fly on wings. However, when you have completed this seminar, you will be able to understand that cars fly on their tires. You will also be able to appreciate that aerodynamics is important not only for drag reduction, but also for increasing cornering speeds and lateral stability. You will be able to correlate between a race car shape and the aerodynamics effects intended for influencing performance. And if you have been a fan of the Ferrari 458 Italia, you will be able to figure out what that black moustache in the front of the car was for.

AA 113. Aerospace Computational Science. 3 Units.
Computational methods are pervasive in analysis, design and optimization of aerospace systems. This course introduces the fundamental concepts underlying aerospace computational science. Starting from the concepts of meshes, elements and point clouds, interpolation, quadrature and time integration, the techniques of finite difference, finite volume and finite element discretization of general PDE problems, and analysis of the accuracy, consistency and stability of discretized problems including treatment of boundary conditions are developed. In depth applications to computations of ideal subsonic, transonic and supersonic flows, and viscous internal and external flow with a turbulence model are introduced. Through the use of commercial and research software (ANSYS Fluent, SU2 and AERO Suite) the student is exposed to the use of computational tools for solving practical aerospace engineering problems. The course culminates with the treatment of multidisciplinary aerospace problems involving coupling across more than one discipline, such as aero-thermal analysis (for hypersonic vehicle performance analysis or gas turbine blade cooling), fluid-structure interaction problems (such as flutter or flapping wing aeroelastic performance), and aeroacoustics (such as jet noise for next generation commercial supersonic transport or noise radiation from multi-rotor urban air mobility platform). Students are expected to pursue significant computational projects in two-person teams. nPrerequisites: CME102, CME104 (multivariable calculus, linear algebra, ODEs and some PDEs), ENGR 14, ME 30, ME70, and Recommended courses: AA102, AA103.

AA 115Q. The Global Positioning System: Where on Earth are We, and What Time is It?. 3 Units.
Preference to freshmen. Why people want to know where they are: answers include cross-Pacific trips of Polynesians, missile guidance, and distraught callers. How people determine where they are: navigation technology from dead-reckoning, sextants, and satellite navigation (GPS). Hands-on experience. How GPS works; when it does not work; possibilities for improving performance.

AA 116Q. Electric Automobiles and Aircraft. 3 Units.
Transportation accounts for nearly one-third of American energy use and greenhouse gas emissions and three-quarters of American oil consumption. It has crucial impacts on climate change, air pollution, resource depletion, and national security. Students wishing to address these issues reconsider how we move, finding sustainable transportation solutions. An introduction to the issue, covering the past and present of transportation and its impacts; examining alternative fuel proposals; and digging deeper into the most promising option: battery electric vehicles. Energy requirements of air, ground, and maritime transportation; design of electric motors, power control systems, drive trains, and batteries; and technologies for generating renewable energy. Two opportunities for hands-on experiences with electric cars. Prerequisites: Introduction to calculus and Physics AP or elementary mechanics.

AA 118N. How to Design a Space Mission: from Concept to Execution. 3 Units.
Space exploration is truly fascinating. From the space race led by governments as an outgrowth of the Cold War to the new era of space commercialization led by private companies and startups, more than 50 years have passed, characterized by great leaps forward and discoveries. We will learn how space missions are designed, from concept to execution, based on the professional experience of the lecturer and numerous examples of spacecraft, including unique hardware demonstrations by startups of the Silicon Valley. We will study the essentials of systems engineering as applicable to a variety of mission types, for communication, navigation, science, commercial, and military applications. We will explore the various elements of a space mission, including the spacecraft, ground, and launch segments with their functionalities. Special emphasis will be given to the design cycle, to understand how spacecraft are born, from the stakeholders' needs, through analysis, synthesis, all the way to their integration and validation. We will compare the current designs with those employed in the early days of the space age, and show the importance of economics in the development of spacecraft. Finally, we will brainstorm startup ideas and apply the concepts learned to a notional space mission design as a team.

AA 119N. 3D Printed Aerospace Structures. 3 Units.
The demand for rapid prototyping of lightweight, complex, and low-cost structures has led the aerospace industry to leverage three-dimensional (3D) printing as a manufacturing technology. For example, the manufacture of aircraft engine components, unmanned aerial vehicle (UAV) wings, CubeSat parts, and satellite sub-systems have recently been realized with 3D printing and other additive manufacturing techniques. In this freshman seminar, a survey of state-of-the-art 3D printing processes will be reviewed and the process-dependent properties of 3D-printed materials and structures will be analyzed in detail. In addition, the advantages and disadvantages of this manufacturing approach will be debated during class! To give students exposure to 3D printing systems in action, tours of actual 3D printing facilities on campus (Stanford's Product Realization Laboratory), as well as in Silicon Valley (e.g., Made in Space) will be conducted.

AA 120Q. Building Trust in Autonomy. 3 Units.
Major advances in both hardware and software have accelerated the development of autonomous systems that have the potential to bring significant benefits to society. Google, Tesla, and a host of other companies are building autonomous vehicles that can improve safety and provide flexible mobility options for those who cannot drive themselves. On the aviation side, the past few years have seen the proliferation of unmanned aircraft that have the potential to deliver medicine and monitor agricultural crops autonomously. In the financial domain, a significant portion of stock trades are performed using automated trading algorithms at a frequency not possible by human traders. How do we build these systems that drive our cars, fly our planes, and invest our money? How do we develop trust in these systems? What is the societal impact on increased levels of autonomy?.

AA 121Q. It IS Rocket Science!. 3 Units.
It's an exciting time for space exploration. Companies like SpaceX and Blue Origin are launching rockets into space and bringing them back for reuse. NASA is developing the world's most powerful rocket. Startups are deploying constellations of hundreds of cubesats for communications, navigation, and earth monitoring. The human race has recently gotten a close look at Pluto, soft landed on a comet, and orbited two asteroids. The upcoming launch of the James Webb Space Telescope will allow astronomers to look closer to the beginning of time than ever before. The workings of space systems remain mysterious to most people, but in this seminar we'll pull back the curtain for a look at the basics of "rocket science." How does a SpaceX rocket get into space? How do Skybox satellites capture images for Google Earth? How did the New Horizons probe find its way to Pluto? How do we communicate with spacecraft that are so distant? We'll explore these topics and a range of others during the quarter. We'll cover just enough physics and math to determine where to look in the sky for a spacecraft, planet, or star. Then we'll check our math by going outside for an evening pizza party observing these objects in the night sky. We'll also visit a spacecraft production facility or Mission Operations Center to see theory put into practice.

AA 122N. Dawn of the Drones: How Will Unmanned Aerial Systems Change Our World?. 3 Units.
Unmanned aerial systems (UASs) have exploded on the scene in recent years, igniting a national debate about how to use them, how to regulate them, and how to make them safe. This seminar will dive into the many engineering challenges behind the headlines: in the future, how will we engineer UASs ranging in size from simple RC toys to highly-sophisticated autonomous scientific and military data gathering systems? This seminar will examine the key elements required to conceive, implement, deploy, and operate state-of-the-art of drone systems: What variety of problems can they help us solve? How autonomous are they and how autonomous do they need to be? What are the key technical bottlenecks preventing widespread deployment? How are they different from commercial aircraft? What kinds of companies will serve the market for UAV-related products and services? What business models will be successful and why? We will emphasize aspects of design, autonomy, reliability, navigation, sensing, and perception, as well as coordination/collaboration through a series of case studies drawn from our recent experience. Examples include imaging efforts to map the changing coral reefs in the South Pacific, using and controlling swarms of unmanned systems to perform search and rescue missions over large areas, and package delivery systems over large metropolitan areas. Hands-on experience with Stanford-developed UASs will be part of the seminar.

AA 131. Space Flight. 3 Units.
This class is all about how to build a spacecraft. It is designed to introduce undergraduate engineering students to the engineering fundamentals of conceiving, designing, implementing, and operating satellites and other space systems. Topics include orbital dynamics, attitude dynamics, mission design, and subsystem technologies. The space environment and the seven classic spacecraft subsystems - propulsion, attitude control and navigation, structure, thermal, power, telemetry and command, and payload - will be explored in detail. Prerequisites: Freshman-level physics, basic calculus and differential equations.

AA 135. Introduction to Space Policy. 3 Units.
The last decade has seen dramatic developments and a rekindling of interest in space efforts. Silicon Valley has invested in a range of activities, including reusable launch services, constellations of communication and observation satellites, off-planet resource development, and even space tourism. Governments are restructuring their space-oriented military and regulatory agencies. Scientific missions continue to benefit from advances in technology, extending the reach and capabilities of robotic missions. Human missions will finally revisit deep space after decades spent solely in low earth orbit. nnThis course investigates the economic, policy, and engineering challenges to building a thriving private and public space industry. We begin with a review of historical space efforts, both public and private. We will investigate current efforts in detail, including budgeting, regulatory frameworks, and the key drivers of the renewed space activity. Externalities provide a core rationale for governmental policy action, including such topics as conflicts over spectrum used by space assets, stimulating innovation, orbital debris challenges, dual-use space technologies, and unclear or conflicting rights to develop space-based resources. Leaders from government and new space companies will occasionally participate in the class.nnStudents will be expected to participate in policy and case discussions, contribute several papers including a final project paper, and complete problem and policy analyses. Readings will include articles, policy papers, HBS cases, regulatory filings, and mission reviews.
Same as: PUBLPOL 131

AA 136A. Spacecraft Design. 4 Units.
The design and implementation of unmanned spacecraft and spacecraft subsystems emphasizing identification of design drivers, current design methods, hands-on experience. The focus will be on the emerging nano-satellite platforms. For 2021, each student will have a CubeSat kit from which practical experiments and subsystems will be developed. Topics: spacecraft configuration design, modern project management approaches, mechanical design, structure and thermal subsystem design, attitude control, electric power, command and telemetry, design integration and operations ¿ as applied to current nano-satellite missions in Low Earth Orbit (LEO) and beyond.nnRequired for Aero/Astro majors. Intended for AA seniors and graduate students. For all other majors consent of instructor is required. Student's mailing address is required to ship CubeSat kit.
Same as: AA 236A

AA 136B. Spacecraft Design Laboratory. 3-5 Units.
Space Capstone II. Required for Aero/Astro majors. Continuation of 236A. Emphasis is on practical application of systems engineering to the life cycle program of spacecraft design, testing, launching, and operations. Prerequisite: 236A or consent of instructor.
Same as: AA 236B

AA 141. Atmospheric Flight. 3 Units.
From people's initial dreams and theories of flight to future design problems, this class introduces students to flight in the atmosphere and the multidisciplinary challenges of aircraft design. We will discuss how new approaches to airplane propulsion, structures, autonomy, and aerodynamics can lead to environmentally sustainable future transportation, supersonic flight, and personal air vehicles. We will look at how local companies are developing autonomous aircraft, inspired by natural flyers, to systems that will provide ubiquitous internet access flying at twice the altitude of airliners. Prerequisites: MATH 20, 21 or equivalents; elementary physics.

AA 146A. Aircraft Design. 4 Units.
Air Capstone I. Required for Aero/Astro majors. This course will be taught entirely online. This capstone design class allows students to apply knowledge from prior classes in a way that emphasizes the interactions between disciplines, and demonstrates how theoretical topics are synthesized in the practical design of an aircraft concept. In part A of this two quarter sequence, students will analyze an existing multi-rotor aircraft by examining, modeling, and critiquing its subsystems. Simultaneously, the students will design a new multi-rotor concept to optimize some design criteria (e.g. flight time, speed, agility, lifting capacity). The class will involve modeling the rigid body dynamics, the structure of the airframe, and aerodynamics of the rotors and airframe, as well as considering the electronics, motors, battery, sensors, and feedback control algorithms for the multi-rotor. Kits of materials and tools will be mailed to each student, enabling them to conduct hands-on exercises. nnnPrerequisites:nn1. Math 20, 21 or 41, 42 or equivalentsnn2. Elementary physics, and AA100 or equivalent classesnn3. Additional required AA courses dealing with aero, structures, and controls.

AA 146B. Aircraft Design Laboratory. 3 Units.
Air Capstone II. Required for Aero/Astro majors. This capstone design class brings together the material from prior classes in a way that emphasizes the interactions between disciplines and demonstrates how some of the more theoretical topics are synthesized in practical design of an aircraft concept. The class will address a single problem developed by the faculty and staff. Students will spend two quarters designing a system that addresses the objectives and requirements posed at the beginning of the course sequence. They will work individually and in teams, focusing on some aspect of the problem but exposed to many different disciplines and challenges. The second quarter will focus on the demonstration of a physical system incorporating features of the design solution. This may be accomplished with a set of experiments or a flight demonstration involving data gathering and synthesis of work in a final report authored by the team.
Same as: AA 246X

AA 149. Operation of Aerospace Systems. 1 Unit.
Due to the pandemic, this class will be conducted remotely for Spring 2021, and there will be no in-person tours requiring live attendance.nnThis course provides a connection with the products of aerospace design through the use of tours, guest speakers, flight simulation, and hands-on exposure to systems used by pilots and space mission operators. We discuss real-world experiences with operators of spacecraft and launch vehicles, and we hear from pilots of manned and unmanned aircraft. Skills required to operate systems in the past, present, and future are addressed. Students will also develop an appreciation of the effects of human factors on aviation safety and the importance of space situational awareness. Anticipated tours include an air traffic control facility and a spacecraft operations center. Some class sessions will be off campus tours at local facilities; these will require some scheduling flexibility outside of normal class hours.

AA 151. Lightweight Structures. 3 Units.
The development of lightweight structures aids in enhancing the robustness, efficiency, and cost of aerospace systems. In this course, the theoretical principles used to analyze stress-strain behavior, beam bending, torsion, and thin-walled structures will be reviewed and exercised. In addition, students will study structures under various loading conditions found in real-world applications such as the design of airframes, high-altitude balloons, and solar sails. Students from various disciplines of engineering can benefit from this course. ENGR 14 (Introduction to Solid Mechanics) is a highly recommended prerequisite.

AA 156. Mechanics of Composite Materials. 3 Units.
This course covers topics related to fiber reinforced composites. Students will learn about stress, strain, and design of composite laminates and honeycomb structures. The course will also provide an overview of failure modes and criteria, environmental effects, and manufacturing processes. An individual design project is required of each student, resulting in a usable computer software.

AA 172. GUIDANCE & NAVIGATION. 3 Units.
Position, Navigation and Timing (PNT) is an increasingly critical element of aerospace and autonomous systems from autonomous cars to commercial jets to deep space probes. Analyze how modern navigation systems work including dead reckoning (speed, direction), radio navigation systems (ground based and satellite) and inertial navigation. Examine the safety and secure use of these systems for guiding commercial aviation and autonomous navigation applications. Explore emerging technologies that may affect the capability and design of future aerospace systems including pulsar navigation for deep space missions and cellular and other signals to aid urban navigation of UAVs, self-driving cars and rail. nnPrerequisites: E15 and familiarity with Matlab and Linear Algebra.

AA 173. Flight Mechanics & Controls. 3 Units.
Aircraft flight dynamics, stability, and their control system design; frame transformations, non-linear equations of motion for aircraft; linearization of longitudinal and lateral-directional dynamics; aircraft static longitudinal and lateral/directional stability and control; observability and controllability; PID feedback control; Prerequisites: E15, E105, AA100 and familiarity with MATLAB.

AA 174A. Principles of Robot Autonomy I. 3-5 Units.
Basic principles for endowing mobile autonomous robots with perception, planning, and decision-making capabilities. Algorithmic approaches for robot perception, localization, and simultaneous localization and mapping; control of non-linear systems, learning-based control, and robot motion planning; introduction to methodologies for reasoning under uncertainty, e.g., (partially observable) Markov decision processes. Extensive use of the Robot Operating System (ROS) for demonstrations and hands-on activities. Prerequisites: CS 106A or equivalent, CME 100 or equivalent (for linear algebra), and CME 106 or equivalent (for probability theory).
Same as: AA 274A, CS 237A, EE 260A

AA 174B. Principles of Robot Autonomy II. 3-4 Units.
This course teaches advanced principles for endowing mobile autonomous robots with capabilities to autonomously learn new skills and to physically interact with the environment and with humans. It also provides an overview of different robot system architectures. Concepts that will be covered in the course are: Reinforcement Learning and its relationship to optimal control, contact and dynamics models for prehensile and non-prehensile robot manipulation, imitation learning and human intent inference, as well as different system architectures and their verification. Students will earn the theoretical foundations for these concepts and implement them on mobile manipulation platforms. In homeworks, the Robot Operating System (ROS) will be used extensively for demonstrations and hands-on activities. Prerequisites: CS106A or equivalent, CME 100 or equivalent (for linear algebra), CME 106 or equivalent (for probability theory), and AA 171/274.
Same as: AA 274B, CS 237B, EE 260B

AA 190. Directed Research and Writing in Aero/Astro. 3-5 Units.
For undergraduates. Experimental or theoretical work under faculty direction, and emphasizing development of research and communication skills. Written report(s) and letter grade required; if this is not appropriate, enroll in 199. Consult faculty in area of interest for appropriate topics, involving one of the graduate research groups or other special projects. May be repeated for credit. Prerequisite: consent of student services manager and instructor.

AA 199. Independent Study in Aero/Astro. 1-5 Unit.
Directed reading, lab, or theoretical work for undergraduate students. Consult faculty in area of interest for appropriate topics involving one of the graduate research groups or other special projects. May be repeated for credit. Prerequisite: consent of instructor.

AA 200. Applied Aerodynamics. 3 Units.
Analytical and numerical techniques for the aerodynamic analysis of aircraft, focusing on airfoil theory, finite wing theory, far-field and Trefftz-plane analysis, two-dimensional laminar and turbulent boundary layers in airfoil analysis, laminar-to-turbulent transition, compressibility effects, and similarity rules. Biweekly assignments require MATLAB or a suitable programming language. Prerequisite: undergraduate courses in basic fluid mechanics and applied aerodynamics, AA 210A.

AA 201A. Fundamentals of Acoustics. 3 Units.
Acoustic equations for a stationary homogeneous fluid; wave equation; plane, spherical, and cylindrical waves; harmonic (monochromatic) waves; simple sound radiators; reflection and transmission of sound at interfaces between different media; multipole analysis of sound radiation; Kirchoff integral representation; scattering and diffraction of sound; propagation through ducts (dispersion, attenuation, group velocity); sound in enclosed regions (reverberation, absorption, and dispersion); radiation from moving sources; propagation in the atmosphere and underwater. Prerequisite: first-year graduate standing in engineering, mathematics, sciences; or consent of instructor.

AA 201B. Topics in Aeroacoustics. 3 Units.
Acoustic equations for moving medium, simple sources, Kirchhoff formula, and multipole representation; radiation from moving sources; acoustic analogy approach to sound generation in compact flows; theories of Lighthill, Powell, and Mohring; acoustic radiation from moving surfaces; theories of Curl, Ffowcs Williams, and Hawkings; application of acoustic theories to the noise from propulsive jets, and airframe and rotor noise; computational methods for acoustics. Prerequisite: 201A or consent of instructor.

AA 203. Optimal and Learning-based Control. 3 Units.
Optimal control solution techniques for systems with known and unknown dynamics. Dynamic programming, Hamilton-Jacobi reachability, and direct and indirect methods for trajectory optimization. Introduction to model predictive control. Model-based reinforcement learning, and connections between modern reinforcement learning in continuous spaces and fundamental optimal control ideas.

AA 204. Spacecraft Electric Propulsion. 3 Units.
The fundamentals of electric propulsion for spacecraft, which exists at the junction of traditional fluid dynamics, plasma physics, and aerospace engineering. The design and physics of electrothermal, electrostatic, and electromagnetic propulsion devices. Prerequisites: prior familiarity and experience with electromagnetism (Maxwell's equations, Ohm's law); fluid dynamics (fluid equations, choked flow, nozzles, Mach number); chemistry (stoichiometry, heat of formation, heat of reaction); and orbital dynamics (rocket equation, thrust, specific impulse, delta-v).

AA 205. Rarefied and Ionized Gases. 3 Units.
Compressible, viscous, rarefied, and ionized gas flow models derived from kinetic theory, quantum mechanics, and statistical mechanics. Equilibrium properties and non-equilibrium processes via collisions and radiation. Monte Carlo collision models for non-equilibrium gas dynamics and partially ionized plasmas. Prerequisite: undergraduate courses in fluid mechanics and thermodynamics, ME 362A recommended but not required.
Same as: ME 362C

AA 206. Bio-Aerodynamics. 3 Units.
Topics: flapping flight, low Reynolds number aerodynamics, wing design, flocks, swarms, and dynamic soaring. Readings from current and historical literature dealing with theoretical and observational studies. Applications in aircraft design, and simulation-based problem sets. Prerequisite: course in aerodynamics such as 100, 200A, or 241A.

AA 208. Aerodynamics of Aircraft Dynamic Response and Stability. 3 Units.
Companion to 200A for those interested in control and guidance. Typical vehicles and the technical tradeoffs affecting their design. Equations of motion, stressing applications to dynamic performance, stability, and forced response. Forms and sources for the required aerodynamic data. Response to small disturbances and stability derivatives. Static stability and trim. Review of aerodynamic fundamentals, leading to airload predictions for wings, bodies, and complete aircraft. Paneling and other methods for derivative estimation. Natural motions of the aircraft, and the influence on them of various configuration parameters. Vehicle behavior in maneuvers of small and large amplitudes. Prerequisites: 200A, 210A, or equivalents (may be taken concurrently).

AA 210A. Fundamentals of Compressible Flow. 3 Units.
Topics: development of the three-dimensional, non-steady, field equations for describing the motion of a viscous, compressible fluid; differential and integral forms of the equations; constitutive equations for a compressible fluid; the entropy equation; compressible boundary layers; area-averaged equations for one-dimensional steady flow; shock waves; channel flow with heat addition and friction; flow in nozzles and inlets; oblique shock waves; Prandtl-Meyer expansion; unsteady one-dimensional flow; the shock tube; small disturbance theory; acoustics in one-dimension; steady flow in two-dimensions; potential flow; linearized potential flow; lift and drag of thin airfoils. Prerequisites: undergraduate background in fluid mechanics and thermodynamics.

AA 210B. Fundamentals of Compressible Flow. 3 Units.
Continuation of 210A with emphasis on more general flow geometry. Use of exact solutions to explore the hypersonic limit. Identification of similarity parameters. Solution methods for the linearized potential equation with applications to wings and bodies in steady flow; their relation to physical acoustics and wave motion in nonsteady flow. Nonlinear solutions for nonsteady constant area flow and introduction to Riemann invariants. Elements of the theory of characteristics; nozzle design; extension to nonisentropic flow. Real gas effects in compressible flow. Flows in various gas dynamic testing facilities. Prerequisite: 210A.

AA 212. Advanced Feedback Control Design. 3 Units.
Analysis and design techniques for multivariable feedback systems. State-space concepts, observability, controllability, eigenvalues, eigenvectors, stability, and canonical representations. Approaches for robust feedback control design, chiefly H2, H-infinity, and mu-synthesis. System identification and adaptive control design. Use of computer-aided design with MATLAB. Prerequisite: ENGR 105, ENGR 205. Recommended: Linear algebra (EE 263 or equivalent).

AA 214. Numerical Methods for Compressible Flows. 3 Units.
For M.S.-level graduate students. Covers the hierarchy of mathematical models for compressible flows. Introduction to finite difference, finite volume, and finite element methods for their computation. Ideal potential flow; transonic potential flow; Euler equations; Navier-Stokes equations; representative model problems; shocks, expansions, and contact discontinuities; treatment of boundary conditions; time and pseudo-time integration schemes. Prerequisites: basic knowledge of linear algebra and ODEs (CME 206 or equivalent).

AA 214C. Numerical Computation of Viscous Flow. 3 Units.
Numerical methods for solving parabolic sets of partial differential equations. Numerical approximation of the equations describing compressible viscous flow with adiabatic, isothermal, slip, and no-slip wall boundary conditions. Applications to the Navier-Stokes equations in two and three dimensions at high Reynolds number. Computational problems are assigned. Prerequisite: 214B.

AA 215A. Advanced Computational Fluid Dynamics. 3 Units.
High resolution schemes for capturing shock waves and contact discontinuities; upwinding and artificial diffusion; LED and TVD concepts; alternative flow splittings; numerical shock structure. Discretization of Euler and Navier Stokes equations on unstructured meshes; the relationship between finite volume and finite element methods. Time discretization; explicit and implicit schemes; acceleration of steady state calculations; residual averaging; math grid preconditioning. Automatic design; inverse problems and aerodynamic shape optimization via adjoint methods. Pre- or corequisite: 214B or equivalent.
Same as: CME 215A

AA 215B. Advanced Computational Fluid Dynamics. 3 Units.
High resolution schemes for capturing shock waves and contact discontinuities; upwinding and artificial diffusion; LED and TVD concepts; alternative flow splittings; numerical shock structure. Discretization of Euler and Navier Stokes equations on unstructured meshes; the relationship between finite volume and finite element methods. Time discretization; explicit and implicit schemes; acceleration of steady state calculations; residual averaging; math grid preconditioning. Automatic design; inverse problems and aerodynamic shape optimization via adjoint methods. Pre- or corequisite: 214B or equivalent.
Same as: CME 215B

AA 216. Model Reduction. 3 Units.
Model reduction is an indispensable tool for computational-based design and optimization, statistical analysis, embedded computing, and real-time optimal control. It is also essential for scenarios where real-time simulation responses are desired. This course presents the basic mathematical theory for projection-based model reduction. It is intended primarily for graduate students interested in computational sciences and engineering. The course material described below is complemented by a balanced set of theoretical, algorithmic, and Matlab computer programming homework assignments.nnPrerequisitesnSolid foundations in numerical linear algebra (CME 200 or equivalent).nBasic numerical methods for ODEs (CME 206 or equivalent).
Same as: CME 345

AA 218. Introduction to Symmetry Analysis. 3 Units.
Methods of symmetry analysis and their use in the reduction and simplification of physical problems. Topics: dimensional analysis, phase-space analysis of autonomous systems of ordinary differential equations, use of Lie groups to reduce the order of nonlinear ODEs and to generate integrating factors, use of Lie groups to reduce the dimension of partial differential equations and to generate similarity variables, exact solutions of nonlinear PDEs generated from groups. Mathematica-based software developed by the instructor is used for finding invariant groups of ODEs and PDEs.

AA 222. Engineering Design Optimization. 3-4 Units.
Design of engineering systems within a formal optimization framework. This course covers the mathematical and algorithmic fundamentals of optimization, including derivative and derivative-free approaches for both linear and non-linear problems, with an emphasis on multidisciplinary design optimization. Topics will also include quantitative methodologies for addressing various challenges, such as accommodating multiple objectives, automating differentiation, handling uncertainty in evaluations, selecting design points for experimentation, and principled methods for optimization when evaluations are expensive. Applications range from the design of aircraft to automated vehicles. Prerequisites: some familiarity with probability, programming, and multivariable calculus.
Same as: CS 361

AA 228. Decision Making under Uncertainty. 3-4 Units.
This course is designed to increase awareness and appreciation for why uncertainty matters, particularly for aerospace applications. Introduces decision making under uncertainty from a computational perspective and provides an overview of the necessary tools for building autonomous and decision-support systems. Following an introduction to probabilistic models and decision theory, the course will cover computational methods for solving decision problems with stochastic dynamics, model uncertainty, and imperfect state information. Topics include: Bayesian networks, influence diagrams, dynamic programming, reinforcement learning, and partially observable Markov decision processes. Applications cover: air traffic control, aviation surveillance systems, autonomous vehicles, and robotic planetary exploration. Prerequisites: basic probability and fluency in a high-level programming language.
Same as: CS 238

AA 229. Advanced Topics in Sequential Decision Making. 3-4 Units.
Survey of recent research advances in intelligent decision making for dynamic environments from a computational perspective. Efficient algorithms for single and multiagent planning in situations where a model of the environment may or may not be known. Partially observable Markov decision processes, approximate dynamic programming, and reinforcement learning. New approaches for overcoming challenges in generalization from experience, exploration of the environment, and model representation so that these methods can scale to real problems in a variety of domains including aerospace, air traffic control, and robotics. Students are expected to produce an original research paper on a relevant topic. Prerequisites: AA 228/CS 238 or CS 221.
Same as: CS 239

AA 236A. Spacecraft Design. 4 Units.
The design and implementation of unmanned spacecraft and spacecraft subsystems emphasizing identification of design drivers, current design methods, hands-on experience. The focus will be on the emerging nano-satellite platforms. For 2021, each student will have a CubeSat kit from which practical experiments and subsystems will be developed. Topics: spacecraft configuration design, modern project management approaches, mechanical design, structure and thermal subsystem design, attitude control, electric power, command and telemetry, design integration and operations ¿ as applied to current nano-satellite missions in Low Earth Orbit (LEO) and beyond.nnRequired for Aero/Astro majors. Intended for AA seniors and graduate students. For all other majors consent of instructor is required. Student's mailing address is required to ship CubeSat kit.
Same as: AA 136A

AA 236B. Spacecraft Design Laboratory. 3-5 Units.
Space Capstone II. Required for Aero/Astro majors. Continuation of 236A. Emphasis is on practical application of systems engineering to the life cycle program of spacecraft design, testing, launching, and operations. Prerequisite: 236A or consent of instructor.
Same as: AA 136B

AA 236C. Spacecraft Design Laboratory. 3-5 Units.
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AA 240. Analysis of Structures. 3 Units.
Analyses of solid and thin walled section beams, trusses, frames, rings, monocoque and semimonocoque structures. Determination of stresses, strains, and deformations, and failure in structures; structural stability and buckling; material behavior: plasticity and fracture. Emphasis on energy methods and introduction of finite element methods. Prerequisite: ENGR 14 or equivalent.

AA 240B. Analysis of Structures. 3 Units.
Thin plate analysis. Structural stability. Material behavior: plasticity and fracture. Introduction of finite element analysis; truss, frame, and plate structures. Prerequisite: 240A or consent of instructor.

AA 241A. Introduction to Aircraft Design, Synthesis, and Analysis. 3 Units.
New aircraft systems emphasizing commercial aircraft. Economic and technological factors that create new aircraft markets. Determining market demands and system mission performance requirements; optimizing configuration to comply with requirements; the interaction of disciplines including aerodynamics, structures, propulsion, guidance, payload, ground support, and parametric studies. Applied aerodynamic and design concepts for use in configuration analysis. Application to a student-selected aeronautical system; applied structural fundamentals emphasizing fatigue and fail-safe considerations; design load determination; weight estimation; propulsion system performance; engine types; environmental problems; performance estimation. Direct/indirect operating costs prediction and interpretation. Aircraft functional systems; avionics; aircraft reliability and maintainability. Prerequisite: 100 or equivalent.

AA 241B. Introduction to Aircraft Design, Synthesis, and Analysis. 3 Units.
New aircraft systems emphasizing commercial aircraft. Economic and technological factors that create new aircraft markets. Determining market demands and system mission performance requirements; optimizing configuration to comply with requirements; the interaction of disciplines including aerodynamics, structures, propulsion, guidance, payload, ground support, and parametric studies. Applied aerodynamic and design concepts for use in configuration analysis. Application to a student-selected aeronautical system; applied structural fundamentals emphasizing fatigue and fail-safe considerations; design load determination; weight estimation; propulsion system performance; engine types; environmental problems; performance estimation. Direct/indirect operating costs prediction and interpretation. Aircraft functional systems; avionics; aircraft reliability and maintainability. Prerequisite: 100 or equivalent.

AA 242A. Classical Dynamics. 3 Units.
Accelerating and rotating reference frames. Kinematics of rigid body motion; Euler angles, direction cosines. D'Alembert's principle, equations of motion. Inertia properties of rigid bodies. Dynamics of coupled rigid bodies. Lagrange's equations and their use. Dynamic behavior, stability, and small departures from equilibrium. Prerequisite: ENGR 15 or equivalent.

AA 242B. Mechanical Vibrations. 3 Units.
For M.S.-level graduate students. Covers the vibrations of discrete systems and continuous structures. Introduction to the computational dynamics of linear engineering systems. Review of analytical dynamics of discrete systems; undamped and damped vibrations of N-degree-of-freedom systems; continuous systems; approximation of continuous systems by displacement methods; solution methods for the Eigenvalue problem; direct time-integration methods. Prerequisites: AA 242A or equivalent (recommended but not required); basic knowledge of linear algebra and ODEs; no prior knowledge of structural dynamics is assumed.
Same as: ME 242B

AA 244A. Introduction to Plasma Physics and Engineering. 3 Units.
Physics and engineering of plasmas, including space and laboratory plasmas. Debye length and distribution functions. Single-particle motion and drifts. Plasmas as fluids and fluid drifts. Waves in plasmas, including electrostatic and electromagnetic. Diffusion and resistivity. Magnetohydrodynamics.

AA 244B. Advanced Plasma Physics and Engineering. 3 Units.
Plasma waves and instabilities. Kinetic theory and the Vlasov equation. Nonlinear effects and solutions. Plasma diagnostics in ground- and space-based experiments. Computational plasma simulation techniques, including particle-in-cell methods, boundary conditions, and field solvers. Prerequisites: AA 244A or consent of instructor.

AA 246X. Aircraft Design Laboratory. 3 Units.
Air Capstone II. Required for Aero/Astro majors. This capstone design class brings together the material from prior classes in a way that emphasizes the interactions between disciplines and demonstrates how some of the more theoretical topics are synthesized in practical design of an aircraft concept. The class will address a single problem developed by the faculty and staff. Students will spend two quarters designing a system that addresses the objectives and requirements posed at the beginning of the course sequence. They will work individually and in teams, focusing on some aspect of the problem but exposed to many different disciplines and challenges. The second quarter will focus on the demonstration of a physical system incorporating features of the design solution. This may be accomplished with a set of experiments or a flight demonstration involving data gathering and synthesis of work in a final report authored by the team.
Same as: AA 146B

AA 250. Nanomaterials for Aerospace. 3 Units.
Properties of nanomaterials and current approaches for engineering spacecraft, aircraft, and subsystems with nanotechnology. Manufacturing of nanomaterials; nano-fiber reinforced composites; structural mechanics of nanomaterials; structure-property relationships; and application of nanotechnology for lightweight structures, thermal protection, nanopropellants, and nanoelectronics.

AA 251. Introduction to the Space Environment. 3 Units.
The environment through which space probes and vehicles travel and orbit. Survey of physical phenomena in the sun, solar wind, magnetospheres, ionospheres, and upper atmospheres of objects in the solar system. Introduction to the physical processes governing space plasmas, solar-terrestrial interactions, and ionized and neutral media surrounding the Earth and other solar system bodies. Prerequisite: AA 244A.

AA 252. Techniques of Failure Analysis. 3 Units.
Introduction to the field of failure analysis, including fire and explosion analysis, large scale catastrophe projects, traffic accident reconstruction, aircraft accident investigation, human factors, biomechanics and accidents, design defect cases, materials failures and metallurgical procedures, and structural failures. Product liability, failure modes and effects analysis, failure prevention, engineering ethics, and the engineer as expert witness.

AA 256. Mechanics of Composites. 3 Units.
Fiber reinforced composites. Stress, strain, and strength of composite laminates and honeycomb structures. Failure modes and failure criteria. Environmental effects. Manufacturing processes. Design of composite structures. Individual design project required of each student, resulting in a usable computer software. Prerequisite: ME 80 or equivalent.

AA 257. Structural Health Monitoring. 3 Units.
Structural health monitoring (SHM) is an emerging technology that provides high-resolution real-time state-sensing, awareness, and self-diagnostic capabilities of structures in service enabled by different types of sensors. SHM is a technology that is designed to interface with the industrial internet of things (IIoT) environment (a) to extend the duration of the service life; (b) to increase the reliability; (c) to reduce the maintenance cost and operational cost. The course will provide in-depth knowledge of two basic damage detection methods for SHM, (a) active sensing and (b) passive sensing. This course will also discuss different kinds of smart materials and sensors, including piezoelectric materials as sensing and actuating elements to interrogate the structures. Advanced signal processing techniques and different types of diagnostics techniques will be discussed and applied to various damage scenarios for qualitative and quantitative measurements. The class will involve structural dynamics, wave propagation, signal processing, finite element methods, and study test cases. Prerequisite: 240 or consent of instructor.

AA 260. Sustainable Aviation. 3 Units.
Quantitative assessment of the impact of aviation on the environment including noise, local, and global emissions, and models used to predict it. Current and future technologies that may allow the air transportation system to meet anticipated growth while reducing or minimizing environmental problems. Atmospheric effects of NOx, CO_2, particulates, unburned hydrocarbons, and water vapor deposition at high altitudes and metrics for assessing global climate effects. Noise sources, measurement, and mitigation strategies. Fundamentals of aircraft and engine performance needed to assess current and future concepts. Major national and international policy implications of existing and future technology choices. Recommended: AA 241B.

AA 261. Building an Aerospace Startup from the Ground Up. 3 Units.
Silicon Valley has experienced a dramatic increase in aerospace-focused, venture capital-backed companies over the last decade. This course will examine what drives success and failure in these ventures, with applicability to prospective founders, employees, investors, or those with a general interest in understanding how real companies operate on a day-to-day basis. The course will cover the entire life cycle of aerospace startups, from idea to product, first financing to exit. Half of the class sessions will be lectures focused on the nuts and bolts of building an aerospace startup. The other sessions will explore critical decision making of recent aerospace startups, through case studies. Often, the protagonists from the case studies will join the class to provide their thinking as they navigated these bet-the-company decisions. Grading will be determined by a combination of hands-on projects and class participation. The instructors are former aerospace entrepreneurs who have raised more than $100 million in capital, launched satellites and derived products from those satellites, and who successfully exited their venture which returned 10x to initial investors.

AA 271A. Dynamics and Control of Aircraft. 3 Units.
The dynamic behavior of aircraft and spacecraft, and the design of automatic control systems for them. For aircraft: non-linear and linearized longitudinal and lateral dynamics; linearized aerodynamics; natural modes of motion; autopilot design to enhance stability, control the flight path, and perform automatic landings. For spacecraft in orbit: natural longitudinal and lateral dynamic behavior and the design of attitude control systems. Prerequisites: AA242A, ENGR 105.

AA 272. Global Positioning Systems. 3 Units.
The principles of satellite navigation using Global Positioning Systems (GPS). Positioning techniques using code tracking, single and dual frequency, carrier aiding, and use of differential and assisted GPS/GNSS for improved accuracy and integrity. Students will learn the building blocks to go from raw received satellite time in nanoseconds all the way to a sophisticated position solution. Using provided Android smartphones, students will collect data and implement an open-ended course project where the goal is to get creative and solve an interesting problem using the tools developed in this course. Prerequisites: familiarity with matrix algebra and MatLab (or another mathematical programming language).

AA 272D. Integrated Navigation Systems. 3 Units.
Navigation satellites (GPS, GLONASS), GPS receivers, principles of inertial navigation for ships, aircraft, and spacecraft. Kalman Filters to integrate GPS and inertial sensors. Radio navigation aids (VOR, DME, LORAN, ILS). Doppler navigation systems. Prerequisites: 272C; ENGR 15, 105. Recommended: ENGR 205.

AA 273. State Estimation and Filtering for Robotic Perception. 3 Units.
Kalman filtering, recursive Bayesian filtering, and nonlinear filter architectures including the extended Kalman filter, particle filter, and unscented Kalman filter. Observer-based state estimation for linear and non-linear systems. Examples from aerospace, including state estimation for fixed-wing aircraft, rotorcraft, spacecraft, and planetary rovers, with applications to control, navigation, and autonomy.

AA 274A. Principles of Robot Autonomy I. 3-5 Units.
Basic principles for endowing mobile autonomous robots with perception, planning, and decision-making capabilities. Algorithmic approaches for robot perception, localization, and simultaneous localization and mapping; control of non-linear systems, learning-based control, and robot motion planning; introduction to methodologies for reasoning under uncertainty, e.g., (partially observable) Markov decision processes. Extensive use of the Robot Operating System (ROS) for demonstrations and hands-on activities. Prerequisites: CS 106A or equivalent, CME 100 or equivalent (for linear algebra), and CME 106 or equivalent (for probability theory).
Same as: AA 174A, CS 237A, EE 260A

AA 274B. Principles of Robot Autonomy II. 3-4 Units.
This course teaches advanced principles for endowing mobile autonomous robots with capabilities to autonomously learn new skills and to physically interact with the environment and with humans. It also provides an overview of different robot system architectures. Concepts that will be covered in the course are: Reinforcement Learning and its relationship to optimal control, contact and dynamics models for prehensile and non-prehensile robot manipulation, imitation learning and human intent inference, as well as different system architectures and their verification. Students will earn the theoretical foundations for these concepts and implement them on mobile manipulation platforms. In homeworks, the Robot Operating System (ROS) will be used extensively for demonstrations and hands-on activities. Prerequisites: CS106A or equivalent, CME 100 or equivalent (for linear algebra), CME 106 or equivalent (for probability theory), and AA 171/274.
Same as: AA 174B, CS 237B, EE 260B

AA 275. Navigation for Autonomous Systems. 3 Units.
Navigation is a key element in many autonomous systems, from self-driving cars to flying robots. In this course you will learn about the technologies that enable autonomous navigation. Topics: navigational system design using GPS as an example; data-driven approach using machine learning and deep learning; model-based approach using probabilistic graph model; theory-based approach using formal verification; intelligent navigational sensor fusion; cyber security and integrity monitoring for localization and navigation. Prerequisites: AA 228 or EE 278; and EE 263 or AA 212. Recommended: AA 272, EE 261, AA 273.

AA 277. Multi-Robot Control and Distributed Optimization. 3 Units.
Survey of current research topics in multi-robot systems including multi-agent consensus, formation control, coverage control and sensor deployment, collision avoidance, cooperative mapping, and distributed Bayesian filtering. Students will develop skills in evaluating and critiquing research papers, and will conduct a final research project.

AA 279A. Space Mechanics. 3 Units.
Orbits of near-earth satellites and interplanetary probes; relative motion in orbit; transfer and rendezvous; orbit determination; influence of earth's oblateness; sun and moon effects on earth satellites; decay of satellite orbits; invited lectures from industry. Prerequisite: ENGR 15 and familiarity with MatLab.

AA 279B. Advanced Space Mechanics. 3 Units.
Restricted 3-body problem. Relative motion, Hill's and Clohessy-Wiltshire equations. Lambert's problem. Satellite constellations and optimization. Communications and link budgets. Space debris. High fidelity simulation. Interplanetary mission planning, launch windows and gravity assists. Basic trajectory optimization. Several guest lectures from practitioners in the field. Individual final project chosen in consultation with instructor. Prerequisites: 279A or equivalent with permission of instructor. Fluency with MATLAB (or another mathematical programming language with 2D and 3D plotting capabilities).

AA 279C. Spacecraft Attitude Determination and Control. 3 Units.
Attitude representation and parametrization; unperturbed and perturbed attitude dynamics and stability; attitude sensors and actuators; linear and nonlinear attitude control; optimal attitude maneuvers; dynamics of flexible spacecraft and space tethers; invited lectures from industry. Prerequisites: AA 242A, ENGR 105, AA 279A, and familiarity with MatLab.

AA 279D. Spacecraft Formation-Flying and Rendezvous. 3 Units.
Keplerian orbital mechanics and orbital perturbations; the general relative motion problem; linear formation flying dynamics and control; impulsive station-keeping and reconfiguration; high order relative motion equations; formulation of relative motion using orbital elements; perturbation-invariant formations; nonlinear formation control; low-thrust propulsion for formation flying; relative navigation using GNSS and optical navigation; applications: sparse-aperture imaging, remote sensing, on-orbit servicing, rendezvous, and docking. Prerequisite: AA 242A, ENGR 105, AA 279A, and familiarity with MatLab.

AA 280. Smart Structures. 3 Units.
Mechanics of smart materials and current approaches for engineering smart structures to monitor health, self heal, and adapt to environment. Definition of smart structures; constitutive models for smart materials; piezoelectric ceramics; electro-active polymers; shape memory alloys; bio-inspired materials and structures; self-healing materials; sensors and sensor networks; structural health monitoring; and energy harvesting. Prerequisite: AA 240A or consent of instructor.

AA 283. Aircraft and Rocket Propulsion. 3 Units.
Introduction to the design and performance of airbreathing and rocket engines. Topics: the physical parameters used to characterize propulsion system performance; gas dynamics of nozzles and inlets; cycle analysis of ramjets, turbojets, turbofans, and turboprops; component matching and the compressor map; introduction to liquid and solid propellant rockets; multistage rockets; hybrid rockets; thermodynamics of reacting gases. Prerequisites: undergraduate background in fluid mechanics and thermodynamics.

AA 284A. Advanced Rocket Propulsion. 1-3 Unit.
The principles of rocket propulsion system design and analysis. Fundamental aspects of the physics and chemistry of rocket propulsion. Focus is on the design and analysis of chemical propulsion systems including liquids, solids, and hybrids. Nonchemical propulsion concepts such as electric and nuclear rockets. Launch vehicle design and optimization issues including trajectory calculations. Limited enrollment. Prerequisites: 283 or consent of instructor.

AA 284B. Propulsion System Design Laboratory. 3 Units.
Propulsion systems engineering through the design and operation of a sounding rocket. Students work in small teams through a full project cycle including requirements definition, performance analysis, system design, fabrication, ground and flight testing, and evaluation. Prerequisite: 284A and consent of instructor.

AA 284C. Propulsion System Design Laboratory. 3 Units.
Continuation of 284A,B. Prerequisite: 284B, and consent of instructor.

AA 289. Robotics and Autonomous Systems Seminar. 1 Unit.
Seminar talks by researchers and industry professionals on topics related to modern robotics and autonomous systems. Broadly, talks will cover robotic design, perception and navigation, planning and control, and learning for complex robotic systems. May be repeated for credit. Same as: CS 529

AA 290. Problems in Aero/Astro. 1-5 Unit.
(Undergraduates register for 190 or 199.) Experimental, theoretical, or computational investigation. Students may work in any field of special interest. This course is designed to develop students' understanding of what a research problem is and the skills needed to successfully approach and conduct research. Register in Axess for section belonging to your research supervisor once the faculty member agrees to supervise your independent study. May be repeated for credit.

AA 290S. Problems in Aero/Astro. 1-15 Unit.
(Undergraduates register for 190 or 199.) Experimental, theoretical, or computational investigation. Students may work in any field of special interest. This course is designed to develop students' understanding of what a research problem is and the skills needed to successfully approach and conduct research. Register in Axess for section belonging to your research supervisor once the faculty member agrees to supervise your independent study. May be repeated for credit.

AA 291. Practical Training. 1-3 Unit.
Educational opportunities in high-technology research and development labs in aerospace and related industries. Internship integrated into a student's academic program. Research report outlining work activity, problems investigated, key results, and any follow-on projects. Meets the requirements for Curricular Practical Training for students on F-1 visas. Student is responsible for arranging own employment and should see department student services manager before enrolling. May be repeated for credit.

AA 294. Case Studies in Aircraft Design. 1 Unit.
Presentations by researchers and industry professionals. Registration for credit optional. May be repeated for credit.

AA 295. Aerospace Structures and Materials. 1 Unit.
Presentations by researchers and industry professionals in aerospace structures and materials. May be repeated for credit.

AA 297. Seminar in Guidance, Navigation, and Control. 1 Unit.
For graduate students with an interest in automatic control applications in flight mechanics, guidance, navigation, and mechanical design of control systems; others invited. Problems in all branches of vehicle control, guidance, and instrumentation presented by researchers on and off campus. Registration for credit optional. May be repeated for credit.

AA 300. Engineer Thesis. 1-15 Unit.
Thesis for degree of Engineer. Students register for section belonging to their thesis adviser.

AA 301. Ph.D. Dissertation. 1-15 Unit.
Prerequisite: completion of Ph.D qualifying exams. Students register for section belonging to their thesis adviser. (Staff).

AA 801. TGR Engineer Thesis. 0 Units.
Engineer's thesis or non-doctoral work for a TGR student.

AA 802. TGR Ph.D. Dissertation. 0 Units.
Doctoral dissertation for a TGR student in PhD program.