Doctoral Field Exam Content
Aeronautics & Astronautics
MIT

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This document describes the field exams that will be offered as of January 2019. A student seeking entrance into the Doctoral Program in the Department of Aeronautics & Astronautics must take one of these field exams. The current list of field exams is:

- o Aerospace computational engineering
- o Aerospace, energy and the environment
- o Air-breathing propulsion
- o Aircraft systems engineering
- o Air transportation systems
- o Autonomous systems
- o Communications and networking
- o Control
- o Humans in aerospace
- o Materials and structures
- o Space propulsion
- o Space systems

The standard for passing the field exam is the demonstration of superior intellectual ability through skillful use of concepts, including synthesis of multiple concepts, in foundational, graduate-level material in a field of aerospace engineering. Note that the field exam descriptions include listings of subjects that cover the exam content. **Students are not required to take these subjects.** Students will make their choice of which field exam and any electives within the chosen exam at the time they apply to take the field exam.

Questions about specific fields may be addressed to faculty involved in the fields. These faculty are listed with the description of each field's exam.

Aerospace Computational Engineering
Faculty involved: Darmofal, Drela, Harris, Marzouk, Peraire, Radovitzky, Wang

Core content (required of every student):
- Numerical methods for ordinary differential equations including consistency, convergence, stability (asymptotic and absolute), local and global accuracy. (16.910)
- Finite difference methods for elliptic, parabolic and hyperbolic PDEs including convergence analysis (16.920)
- Finite volume methods for nonlinear hyperbolic PDEs (16.920)
- Finite element methods for elliptic problems, variational formulation and analysis (16.920)
- Boundary integral equation methods (16.920)
- Direct solution methods for sparse linear systems of equations (16.910 or 18.335)
- Iterative methods for linear systems of equations (16.910 and 18.335)
- Methods for nonlinear systems of equations (16.910)
- Basics of multigrid methods (16.920)
- The singular value decomposition, QR factorization, and least squares problems (18.335)
- Gaussian elimination and LU factorization (18.335)
- Eigenvalue problems (18.335)
- Iterative methods for eigenvalue problems (18.335)

Elective content (each student selects one of the following four electives):
A. Fluid mechanics
- Control volume theorems and applications (2.25)
- Dimensional analysis and flow similarity (2.25 or 16.13)
- Incompressible potential flow theory (2.25 or 16.110)
- Laminar boundary layers (2.25 or 16.13)
- Vorticity and circulation (2.25 or 16.110)

B. Mechanics of solid materials
- Theory of elasticity: linear isotropic thermo-elasticity, variational and energy methods (2.071)
- Linear viscoelasticity (2.071)
- Small strain isotropic plasticity (2.071)
- Finite deformation elasticity: kinematics of deforming bodies, strain measures, balance laws, stress measures, hyperelastic constitutive theory (2.071)

C. Optimization methods
- Linear optimization and duality theory (15.093)
- Optimality conditions and gradient methods for nonlinear unconstrained optimization (15.093)
- Constrained optimization and Lagrange multipliers (15.093)
- Line searches and Newton's method (15.093)
- Introduction to semidefinite optimization (15.093)

D. Applied probability
- Random variables; probability distributions and densities; expectation and conditioning (6.431)
- Laws of large numbers, central limit theorems (6.431)
- Multivariate Gaussian distributions (6.431)
- Markov chains (6.431)
- Monte Carlo methods (16.90)

Aerospace, Energy and the Environment
Faculty Involved: Balakrishnan, Barrett, Drela, Guerra Garcia, Greitzer, Hansman, Peraire, Sabnis, Spakovszky, Waitz

Coming soon – please see AEN Field Description for more information.

Air-breathing Propulsion
Faculty involved: Drela, Greitzer, Spakovszky, Waitz

<u>Core content (required of every student)</u>
- o Control volume theorems and applications (2.25, 16.540, 16.120)
- o Dimensional analysis and flow similarity (2.25)
- o Incompressible potential flow theory (2.25)
- o Laminar boundary layers (2.25, 16.13)
- o Vorticity and circulation (2.25, 16.540)
- o Turbomachinery aerodynamics and heat transfer (16.511)
- o Gas turbine engine component performance (16.511)
- o Gas turbine engine aerodynamic and thermodynamic performance (16.511)

<u>Elective content (each student selects one of the following two electives):</u>

A. Compressible flow
- o "Classical" one-dimensional compressible flow (16.120, 2.26)
- o Application of control volume analyses in compressible flows (16.120)
- o Swirling one-dimensional compressible flow (16.120)
- o Compound-compressible flow [non-uniform quasi one-dimensional compressible flow] (16.120)
- o Flow processes in propulsion systems (16.120, 16.512)

B. Internal flow in turbomachines
- o Vorticity and circulation (2.25,16.540)
- o Flow in rotating passages (16.540)
- o Loss sources and loss accounting in propulsion components and systems and in fluid machinery (16.540)
- o Unsteady flow (16.540, 16.543)

Aircraft Systems Engineering
Faculty involved: Drela, Hansman, Harris, Lagace, Leveson, Liebeck

The following content will be assessed in the Aircraft Systems field exam:

Core content (required of every student) (16.885J or 16.886)
- System requirements analysis and flowdown
- Dynamics
- Aircraft performance
- Trade space and optimization
- Multidisciplinary optimization

Elective content (each student selects 2 areas from the following sets of topics):

A. Aerodynamics (16.110)
- Behavior of skin friction for laminar and turbulent boundary layers and its dependence on Reynolds number
- Airfoil drag as a function of Reynolds number and Mach number
- Induced drag and span efficiency
- Airplane drag polars
- Experimental testing

B. Aircraft instrumentation (16.343)
- Electromagnetic waves
- Measurement theory and error
- Bandwidth considerations
- Signal-to-Noise Ratio
- Navigation systems
- Remote sensing system
- Sensor physics

C. Aircraft propulsion (16.511)
- Performance and characteristics of turbojet, turbofan, and turboprop engines
- Thermodynamic behavior and cycles
- Fluid mechanic behavior of inlets, compressors, combustors, turbines, and nozzles.

D. Aircraft stability and control (16.333)
- Static stability and trim
- Stability derivatives and characteristic longitudinal and lateral-directional motions.
- Physical effects of wing, fuselage, and tail on aircraft motion. Flight vehicle stabilization by classical and modern control techniques.
- Time and frequency domain analysis of control system performance.
- Human pilot models and pilot-in-the-loop control with applications.

E. Aircraft structures (2.071)
- Kinematics of deformation
- Stress
- Balance principles
- Isotropic linear elasticity and isotropic linear thermal elasticity.

- o Variational and energy methods
- o Linear viscoelasticity
- o Small-strain elastic-plastic deformation
- o Mechanics of large deformation

F. Human factors (16.453, 16.422)
- o Interaction of humans with aircraft and space vehicles
- o Manual control
- o Human-computer interaction
- o Human error causes
- o Sensory, motor, and cognitive performance characteristics
- o Allocation of roles and authority between humans and automation

G. Software systems (16.355J)
- o Software process and lifecycle
- o Requirements and specifications
- o Testing
- o Formal analysis and reviews
- o Quality management and assessment
- o Product and process metrics
- o COTS and reuse
- o Software engineering aspects of programming languages

Air Transportation Systems
Faculty involved: Balakrishnan, Hansman, Belobaba

The following content will be assessed in the Air Transportation field exam. A basic knowledge of probability, queuing theory and optimization (as needed for the analysis of the topics shown below) is also expected. It is expected that all students have taken 16.71J, *in addition to at least one* of the following: 16.781J, 16.72, 16.75J, or 16.763.

In any given year, a subset of these topics will be tested:

o Measures of air traffic demand, capacity and performance
o Airline operations
o Pricing, revenue management and distribution
o Airline operating costs and productivity
o System capacity and delays
o Airport (airside and landside) design
o Demand management
o Air traffic flow management
o Airline scheduling and fleet planning criteria

Autonomous Systems
Faculty involved: How, Karaman, Roy, Shah, Williams, Carlone.

Students will be assessed on the application of models and methods from the **core content** and a **single elective content**, to the design of autonomous systems and decision-making capabilities. Examples include path planning, scheduling, resource allocation, inventory control, activity planning, diagnosis, estimation, stochastic control and system trade analysis. Assessment of the content focuses on the creation of decision systems through architecting, modeling, and algorithmic design and analysis.

Core content (required of every student):
o State space search. Formulation in terms of states, operators, goal states and an initial state. Methods for uninformed search, including depth-first, breadth-first and iterative deepening, and for informed search, including best-first, A* and branch and bound (16.413).

o Sequential decision problems. Formulation as finite and infinite horizon, deterministic and non-deterministic Markov decision processes. Methods for policy construction, including dynamic programming, value iteration and reinforcement learning (16.413).

o Multi-agent and probabilistic planning. Methods for game tree search, including mini-max and alpha-beta pruning, and for And-Or search, including AO* and LAO* (16.413).

o Hidden state estimation. Formulation as a hidden Markov model. Methods for belief state estimation, including filtering, prediction and smoothing (forward-backward), and for trajectory estimation, including the Viterbi algorithm (16.413).

o Constraint and mathematical programming. Formulation using finite domain constraints, linear, binary, integer and mixed program encodings. Methods include constraint propagation, simplex, and systematic tree search, including backtrack search with forward checking, conflict-directed search, and branch and bound (16.413).

o Propositional logic. Problem formulation and semantics, including satisfiability and entailment. Methods for satisfiability and inference, including unit propagation, the DPLL algorithm and clause learning (16.413).

o Probabilistic inference. Formulation using Bayesian network encodings. Methods for Bayesian inference through variable elimination (16.413).

o Decision architectures that combine a subset of activity planning, scheduling, diagnosis, path planning, trajectory optimization and logistics support (16.413).

Elective content (each student **selects one** of the following two electives):

A. Cognitive Robotics (16.412J)

Covers algorithms and paradigms for creating a wide range of human-robot systems that act intelligently and robustly, by reasoning extensively from models of themselves, their counterparts and their world.

o Programming of goal-directed systems. Paradigms for programming, including decision-theoretic, state-

space, model-based and risk-bounded programming. Problem formulation in the Reactive Model-based Programming Language.

o Constraint optimization. Formulation as optimal satisfiability problems and mixed logic linear programs. Optimization methods based on conflict-directed A* and conflict-directed branch and bound.

o Temporal activity planning. Formulation of temporal planning problems. in the Planning Domain Description Language. Methods for planning using heuristic forward search, plan relaxation, causal-graph decomposition and landmark analysis.

o Robust plan execution. Problem formulation using temporal plan networks and temporal constraint networks. Methods for plan selection, dynamic scheduling, execution monitoring and re-planning.

o Mode estimation and diagnosis.   Problem formulation using probabilistic constraint automata. Methods including approximate belief state update and decoding for PCA.

o Decision-making for hybrid systems. Modeling of hybrid discrete and continuous systems as probabilistic hybrid automata and flow tubes. Mixed activity and trajectory planning and state estimation using PHA and flow tubes.

o Human-robot collaboration. Cooperative task execution. Adjusting over-subscribed plans through constraint relaxation.

o Risk-bounded decision-making. Risk-bounded contingency planning, scheduling and motion planning under uncertainty.

B. Stochastic Estimation and Control (16.322)

Covers the estimation and control of dynamical systems.

o Classical and state-space descriptions of random processes and their propagation through linear systems (16.322).

o Kalman filters to estimate the states of dynamic systems and conditions for stability of the filter equations (16.322).

o Application to the design of autonomous systems and decision support systems (16.322).

Communications and Networking
Faculty involved: Modiano, Win

Elective content (each student selects two of the following three topics):

A. Probability and Statistics (6.431, 16.391J)
- o Preliminaries (BT Chapter 1-5)
- o Stochastic processes (BT Chapters 6,7)
- o Principles of data reduction (CB Chapter 6)
- o Point estimation (CB Chapter 7)
- o Hypothesis testing (CB Chapter 8)

B. Data Networks (16.37J)
- o Protocols (BG Chapter 2, class notes)
- o Queueing models (BG Chapter 3)
- o Multiple access (BG Chapter 4)
- o Routing algorithms (BG Chapter 5)
- o Stability of queueing systems (GNT)
- o Stochastic Network Optimization (MJN)

C. Digital Communications (16.393)
- o Power spectral density of digital modulations (SHL Chapter 2)
- o Communications over memoryless channels (SHL Chapter 3)
- o Coherent communications (SHL Chapter 4)
- o Noncoherent communications (SHL Chapter 5)
- o Optimum receiver principles (WJ Chapter 4)

References:

BG: Bertsekas and Gallager, "Data Networks," Prentice-Hall, 1991.
BT: Bertsekas and Tsitsiklis, "Introduction to Probability," 2nd Edition, Athena Scientific, 2008.
CB: Casella and Berger, "Statistical Inference," 2nd ed. CA: Duxbury, 2002.
SHL: Simon, Henedi, and Lindsey, "Digital communication techniques: signal design and detection," Prentice Hall, 1995.
WJ: Wozencraft and Jacobs, "Principles of Communication Engineering," Waveland Press, 1965.
GNT: L Georgiadis, M. J. Neely, L. Tassiulas, "Resource Allocation and Cross-Layer Control in Wireless Networks," Foundations and Trends, NOW publishers, 2006.
MJN: Mike J Neely, "Stochastic Network Optimization with Application to Communication and Queueing Systems,". Morgan and Claypool, 2010.

Controls
Faculty involved: Hall, How, Karaman

All students will be assessed on the following topics:
- System modeling and linear systems theory (stability, model realizations, controllability, observability)
- Classical control design and analysis (root locus, Bode, Nyquist)
- State space control synthesis (pole placement, separation principle)
- Estimation and control for stochastic systems (stochastic systems, Kalman filter, EKF, duality)
- Optimal control design (DP, HJB, LQR, LQG, robustness analysis)

Subjects that cover the above topics at the desired level are:
- Feedback Control Systems (16.31) or Dynamic Systems and Control (6.241)
- Stochastic Estimation and Control (16.322)
- Principles of Optimal Control (16.323)

Humans in Aerospace

Faculty involved: Hansman, Hoffman, Newman, Oman, Shah, Stirling, Young

Core content (required of every student)
- o Sensory systems related to information processing (visual, auditory, vestibular)
- o Displays and controls – principles and cockpit applications
- o Manual control and handling qualities
- o Workload and situational awareness
- o Experimental Design
- o Anthropometry – fitting the workspace to the operator
- o Human-automation interaction

Subject covering this material:
    16.453 (Human Factors Engineering)

Textbooks covering this material:
    R.W. Proctor and T. Van Zandt, *Human Factors in Simple and Complex Systems*, CRC Press, 2008.
    P. S. Tsang and M.A. Vidulich, *Principles and Practice of Aviation Psychology*, Lawrence Erlbaum, Mahwah, NJ, 2003
    Bluman, A.G., *Elementary Statistics, A Step-by-Step Approach*, 3rd Ed., New York: McGraw-Hill, (2003)

Elective content (each student selects the content of one of the following areas):

A. Aerospace biomedical engineering:
- o Space physiology (musculoskeletal, cardiovascular and neurovestibular systems)
- o Control and dynamics applied to astronaut performance
- o Human exploration in extreme environments
- o Extra-Vehicular Activity
- o Life support systems

    Subject covering this material:
        16.423 (Aerospace Biomedical and Life Support Engineering)
    Textbook covering this material
        Buckey, J. B., *Space Physiology,* Oxford U. Press, New York, 2006

B. Humans and automation:
- o Design of supervisory control systems including visual, aural, and haptic considerations
- o Evaluation of supervisory control systems including design of experiments & simulation modeling
- o Social implications of human-automations systems

    Subject covering this material:
        16.422 (Human Supervisory Control of Automated Systems)
    Textbook covering this material:
        Sheridan, T., *Humans & Automation: System Design & Research Issues*, John Wiley & Sons, 2002.

Materials and Structures
Faculty involved: Crawley, Lagace, Radovitzky, Wardle

The following content will be assessed in the Materials and Structures field exam:

- o Three-dimensional linear elasticity theory including various solution methodologies (2.071 or ES240)
- o Anisotropic linear constitutive behavior (2.071 or ES240; and 16.223 or 2.080)
- o Variational and energy methods (2.071 or ES240)
- o First-level treatment of plasticity, viscoelasticity (2.071 or ES240)
- o Thermoelastic solids (2.071 or ES240)
- o Phenomenological description of failure/fracture/fatigue of different classes of materials, including fracture mechanics (3.22)
- o Phenomenological description of constitutive behavior of different classes of materials (2.071 or ES240)
- o Elementary static and buckling problems of one-dimensional and two-dimensional engineering structures (2.080)
- o Dynamic wave and structural dynamic topics (16.221J)
- o First-level treatment of computational mechanics and the finite element method (2.094 or 16.920J)

Space Propulsion

Faculty involved: Hastings, Lozano, Martinez-Sanchez, Miller, Guerra Garcia

The following content will be assessed in the Space Propulsion field exam:

- Engineering and physical principles of electrothermal, electrostatic and electromagnetic propulsion systems; prediction of performance: specific impulse, efficiency and thrust; spacecraft integration: power requirements, contamination, thermal issues. (16.522)
- Rocket propulsion systems: compressible flow, nozzle performance, adiabatic flame temperature, prediction of performance; combustion chambers: gas and turbomachinery pressurization. (16.50 or 16.512)
- Orbital mechanics: launch and orbit insertion, impulsive maneuvers, planetary flybys; low thrust limit: spiral climb, plane change, perturbation of orbital elements, thrust profile optimization. (16.512 or 16.522 or 16.346)
- Classical electrodynamics: Maxwell's equations, electrostatics, magnetostatics, plane waves; fields in dielectric and magnetic materials. (8.02 or 8.022 or 6.641)
- Fundamentals of plasma physics: Debye length, plasma frequency, charged particle drifts, magnetic mirrors, Poisson's and Laplace's fields, electrostatic sheaths, space charge limit. (22.611J or 16.55)
- Elements of kinetic theory: concept of distribution functions; the Maxwellian distribution, Boltzmann equilibrium; the Vlasov equation and the Boltzmann equation. (22.611J or 16.55)
- Thermodynamics: first and second laws and applications; free energies, phase equilibria, combustion thermochemistry. (16.004, 16.512)
- Concepts on numerical solution of ordinary and simple partial differential equations; applications in fluid dynamics, electrodynamics, heat transfer and related fields. (18.03)

Space Systems
Faculty involved: Crawley, de Weck, Hastings, Hoffman, How, Leveson, Miller, Widnall, Williams, Cahoy, Linares

Core content (required of every student):

- o Fundamental principles of Systems Engineering and the "V"-model (stakeholders, requirements, trade spaces, interfaces, testing and integration ...) (16.842)
- o Fundamental design impact associated with the space environment (orbital dynamics, radiation, vacuum, thermal, ...) (16.851)
- o Spacecraft payload technologies and their impact on spacecraft design (RF, optical, communications, radar, ...) (16.851)
- o Spacecraft bus subsystem technologies and their interactions with each other, the payload and the environment (power, structures, GNC, ACS, avionics, ...) (16.851)
- o Issues and design techniques associated with missions involving multiple spacecraft (satellite constellations, close proximity formations, and docking system design) (16.89)

Elective content (each student selects the content of one of the following subjects):

A. Space system architecture and design
- o Space mission architecting (16.892J, 16.89)
- o Design and analysis processes including requirements, stakeholder analysis, and lifecycle costs (16.892J, 16.842)
- o Design of flexibility into the architecture, resolution of uncertainty (technical, economic, etc.) in the architectures (16.892J, 16.861)

B. Space system engineering
- o The lifecycle phases of a typical space program including objectives, milestones, documentation, and processes associated with each phase (16.89J)
- o Processes for design refinement including mission performance modeling, trade analysis, and risk assessment (16.89J)
- o Design team organization including work breakdown structures, scheduling, and resource allocation including budgets and margins (mass, power, cost, etc.) (16.89J)

C. System safety
- o Designing and operating safety-critical systems including the nature of risk, formal accident and human error models, and causes of accidents (16.863J)
- o Safety engineering and design including issues in the design of human-machine interaction (16.863J)
- o System and software hazard analysis, fault tolerance, etc. (16.863J)