

**Doctoral Field Exam Content
Aeronautics & Astronautics
M.I.T.**

October 15, 2008

This document describes the field exams that will be offered in January 2009. 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:

- Aerospace computational engineering
- Air-breathing propulsion
- Aircraft systems engineering
- Air transportation systems
- Autonomous systems
- Communications and networking
- Control
- Humans in aerospace
- Materials and structures
- Space propulsion
- 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, Peraire, Radovitzky, Willcox

Core content (required of every student):

- Direct solution methods for sparse linear systems of equations (16.910 or 18.335)
- Iterative methods for linear systems of equations (16.910 or 18.335)
- Basics of multigrid methods (16.920)
- Methods for nonlinear systems of equations (16.910)
- 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 PDE's including convergence analysis (16.920)
- Finite volume methods for nonlinear hyperbolic PDE's (16.920)
- Finite element methods for elliptic problems, variational formulation and analysis (16.920)
- Boundary integral equation methods (16.920)

Elective content (each student selects two 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. Numerical linear algebra

- 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 linear systems of equations and for eigenvalue problems. (18.335)

D. 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)

Air-breathing Propulsion

Faculty involved: Drela, Epstein, Greitzer, Spakovszky, Waitz

Core content (required of every student)

- Control volume theorems and applications (2.25, 16.540, 16.120)
- Dimensional analysis and flow similarity (2.25)
- Incompressible potential flow theory (2.25)
- Laminar boundary layers (2.25, 16.13)
- Vorticity and circulation (2.25, 16.540)
- Turbomachinery aerodynamics and heat transfer (16.511)
- Gas turbine engine component performance (16.511)
- Gas turbine engine aerodynamic and thermodynamic performance (16.511)

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

A. Compressible flow

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

B. Internal flow in turbomachines

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

Aircraft Systems Engineering

Faculty involved: Drela, Hansman, Harris, Lagace, Leveson, Liebeck, Nightingale, Waitz, Willcox

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.

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

F. Human factors (16.453, 16.422)

- Interaction of humans with aircraft and space vehicles
- Manual control
- Human-computer interaction
- Human error causes
- Sensory, motor, and cognitive performance characteristics
- Live support systems
- Allocation of roles and authority between humans and automation

G. Software systems (16.355J)

- Software process and lifecycle
- Requirements and specifications
- Testing
- Formal analysis and reviews
- Quality management and assessment
- Product and process metrics
- COTS and reuse
- Software engineering aspects of programming languages

Air Transportation Systems

Faculty involved: Balakrishnan, Cummings, Hansman, Odoni, Waitz, Weigel

The following content will be assessed in the Air Transportation field exam:

Core content (required of every student)

- Measures of airline traffic, capacity and performance (16.71J and 16.72)
- Fundamentals of airline demand, markets and competition (16.71)
- Airline operations (16.71J)
- Airline operating costs and productivity (16.71J)
- Airside capacity and delays (16.71J, 16.781J and 16.72)

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

A. Air traffic control

- Basic structure of the National Airspace System, ATC procedures (16.72)
- Air traffic flow management (16.72 and 16.781J)
- Impact of weather on air traffic operations (16.72)
- Terminal-area operations and control (16.72)
- Automation and decision support tools (16.72)

B. Airline management

- Route profitability assessments (16.75J and 16.71J)
- Demand variability and spill modeling (16.75J)
- Fleet planning criteria and evaluation models (16.75J and 16.71J)
- Airline scheduling and fleet assignment optimization (16.71J and 16.75J)
- Pricing, revenue management and distribution (16.75J and 16.71J)

C. Airport systems

- Geometric design of the airfield (16.781J and 16.71J)
- Passenger terminal design and capacity (16.781J and 16.71J)
- Demand management (16.781J and 16.71J)
- Air traffic flow management (16.72 and 16.781J)
- Airport charges and financing (16.781J and 16.71J)

Autonomous Systems

Faculty involved: Frazzoli, Roy, Williams

Core content (required of every student):

- State space search formulation, algorithms and complexity analysis. Methods include uninformed search (e.g., depth-first, breadth-first and iterative deepening), informed search (best-first, branch and bound, and A*) and game tree search (e.g., mini-max and alpha-beta pruning) (16.413).
- Constraint and mathematical programming. Finite domain constraint, linear, binary, integer and mixed program encodings. Methods include simplex, constraint propagation and systematic tree search (e.g., backtrack search with forward checking, backjumping and branch and bound). (16.413).
- Propositional and temporal logics, including problem formulation, semantics (e.g., satisfiability and entailment) and inference (e.g., DPLL algorithm) (16.413).
- Probabilistic reasoning. Bayesian networks and hidden Markov models. Belief state estimation, trajectory estimation (Viterbi algorithm) and model learning (Baum-Welch) (16.413).
- Application of the above models and methods to the design of autonomous systems and decision making capabilities (e.g., path planning, scheduling, resource allocation, inventory control, activity planning, diagnosis, estimation and stochastic control) (16.413).

And questions from either (student chooses one of the following two core topics):

Core option 1: Dynamic programming

- Formulation of sequential decision problems as deterministic, non-deterministic and semi-Markov decision processes. Finite and infinite horizon formulations (6.231).
- Solution to sequential decision problems via dynamic programming, policy iteration, value iteration, rollout and approximate methods (6.231).

Core option 2: Stochastic estimation and control

- Classical and state-space descriptions of random processes and their propagation through linear systems (16.322).
- Frequency domain design of filters and compensators (16.322)
- Kalman filters to estimate the states of dynamic systems and conditions for stability of the filter equations (16.322)

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

- A. Algorithms for estimation and inference: Models and algorithms for estimation and inference, including linear estimation; Karhunen-Loeve expansions; Cholesky decompositions; linear state-space models, Kalman filtering, the RTS algorithm; asymptotics; non-linear extensions and particle filtering; Autoregressive modeling and linear prediction; RLS and Levinson algorithms; Hidden Markov models; forward-backward, Viterbi, and Baum-Welch algorithms; graphical models and belief propagation, and sum-product, min-sum, and junction tree algorithms. (6.438)
- B. Cognitive robotics: Algorithms and paradigms for creating cognitive robots, including deduction and search in real-time; temporal, decision-theoretic and contingency planning; dynamic execution and re-planning; reasoning about hidden state and failures; reasoning under uncertainty; path planning, mapping and localization, and cooperative and distributed robotics (16.412J).

- C. Distributed algorithms: Design and analysis of distributed, concurrent algorithms, including process synchronization, allocation of computational resources, distributed consensus, distributed graph algorithms, leader election, distributed termination, deadlock detection, concurrency control, communication, and clock synchronization (6.852J).
- D. Human factors engineering: Human factors engineering for manual control and human-computer interaction with aircraft and complex machines, including sensory, motor, and cognitive performance models; human engineering design criteria, and principles of displays, control and ergonomics (16.453).
- E. Machine learning: Principles, techniques, and algorithms for machine learning, including statistical inference; representation, generalization, and model selection; linear/additive models; active learning; boosting; support vector machines; hidden Markov models; and Bayesian networks (6.867).
- F. Machine vision: Methods of machine vision for deriving symbolic descriptions from images, including physics of image formation; image analysis as an inversion problem; binary image processing and filtering of images; recovering shape, lightness, orientation, and motion; using constraints to reduce ambiguity, and photometric stereo and extended Gaussian spheres (6.801, 6.866).
- G. Software engineering: Software lifecycle engineering processes, including requirements and specification; design principles; testing, formal analysis, and reviews; quality management and assessment; product and process metrics; COTS and reuse; evolution and maintenance; and team organization and people management (16.355J).
- H. Theory of computation: Computability and computational complexity theory, including regular and context-free languages; decidable and undecidable problems; reducibility and recursive function theory; time and space measures on computation; completeness; hierarchy theorems; inherently complex problems; oracles; probabilistic computation; and interactive proof systems (6.840J).

Communications and Networking

Faculty involved: Modiano, Win

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

A. Applied probability (6.431)

- Preliminaries (BT Chapter 1-3)
- Further topics on random variables (BT Chapter 4)
- Limit theorems (BT Chapter 5)
- The Bernoulli and Poisson processes (BT Chapter 6)
- Markov chains (BT Chapter 7)

B. Data networks (16.37J)

- Link layer protocols (BG Chapter 2)
- Queuing models (BG Chapter 3)
- Multiple access and LANs (BG Chapter 4)
- Routing algorithms (BG Chapter 5)
- TCP/IP and the Internet (16.37 class notes)

C. Principles of digital communication (6.450)

- Power spectral density of digital modulations (SHL Chapter 2)
- Scalar and vector communications over memoryless channel (SHL Chapter 3)
- Coherent communications with waveforms (SHL Chapter 4)
- Noncoherent communication with waveforms (SHL Chapter 5)

D. Principles of wide bandwidth communication (16.395)

- Random waveforms (WJ Chapters 2-3)
- Optimum receiver principles (WJ Chapters 4)
- Spread spectrum concepts (PZB Chapter 2,5,6)
- Ultrawide bandwidth systems (Class notes)

E. Statistics for engineers and scientists (16.391J)

- Bayesian statistical inference (BT Chapter 8)
- Classical statistical inference (BT Chapter 9)
- Hypothesis testing (Class notes)

References:

BG: Bertsekas and Gallager, "Data Networks," Prentice-Hall, 1991.

BT: Bertsekas and Tsitsiklis, "Introduction to Probability," 2nd Edition, Athena Scientific, 2008.

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.

PZB: Peterson, Ziemer, and Borth "An Introduction to Spread-Spectrum Communications" Prentice-Hall, 1995.

Controls

Faculty involved: Deyst, Frazzoli, Hall, How

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)
- Nonlinear control analysis (Jacobian linearization, Lyapunov functions, describing functions)

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: Cummings, Hansman, Hoffman, Newman, Oman, Young

Core content (required of every student)

- Sensory systems related to information processing (visual, auditory, vestibular)
- Displays and controls – principles and cockpit applications
- Manual control and handling qualities
- Pilot workload, including situation awareness
- Fatigue, scheduling and circadian rhythms
- Anthropometry – fitting the workspace to the operator
- Human-automation interfaces
- Crew resource management

Subject covering this material:

16.453 (Human Factors Engineering)

Textbooks covering this material:

P. S. Tsang and M.A. Vidulich, *Principles and Practice of Aviation Psychology*, Lawrence Erlbaum, Mahwah, NJ, 2003

E. L. Wiener and D.C. Nagel, *Human Factors in Aviation*, Academic Press, San Diego, CA, 1988

C. D. Wickens and J. G. Hollands, *Engineering Psychology and Human Performance*, 3rd ed., Prentice Hall, Upper Saddle River, NJ, 2000

Background in Experimental Design and Statistics can be found in 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:

- Space physiology (musculoskeletal, cardiovascular and neurovestibular systems)
- Control and dynamics applied to astronaut performance
- Human exploration in extreme environments
- Extra-Vehicular Activity
- 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:

- Design of supervisory control systems including visual, aural, and haptic considerations
- Evaluation of supervisory control systems including design of experiments & simulation modeling
- 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: Lagace, Radovitzky, Wardle

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

- Three-dimensional linear elasticity theory including various solution methodologies (2.071 or ES240)
- Anisotropic linear constitutive behavior (2.071 or ES240; and 16.223 or 2.080)
- Variational and energy methods (2.071 or ES240)
- First-level treatment of plasticity, viscoelasticity (2.071 or ES240)
- Thermoelastic solids (2.071 or ES240)
- Phenomenological description of failure/fracture/fatigue of different classes of materials, including fracture mechanics (2.075 or 3.35)
- Phenomenological description of constitutive behavior of different classes of materials (2.071 or ES240)
- Elementary static and buckling problems of one-dimensional and two-dimensional engineering structures (2.080)
- Dynamic wave and structural dynamic topics (16.221J)
- First-level treatment of computational mechanics and the finite element method (2.094 or 16.920J)

Space Propulsion

Faculty involved: Epstein, Hastings, Lozano, Martinez-Sanchez, Miller

Note that electives have been removed from the previous subject-based description, leaving exclusively the core content and its requirements as described below:

- 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, Keesee, Leveson, Miller, Weigel, Widnall, Williams

Core content (required of every student):

- Fundamental design impact associated with the space environment (orbital dynamics, radiation, vacuum, thermal, ...) (16.851)
- Spacecraft payload technologies and their impact on spacecraft design (RF, optical, communications, radar, ...) (16.851)
- Spacecraft bus subsystem technologies and their interactions with each other, the payload and the environment (power, structures, GNC, ACS, avionics, ...) (16.851)
- Issues and design techniques associated with missions involving multiple spacecraft (satellite constellations, close proximity formations, and docking system design) (16.851)

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

A. Space policy

- National security, civil and commercial space policy and its historical context (16.891J)
- Space law, including the most important international space treaties (16.891J)
- The role of in-depth technical analysis in supporting critical policy decisions (16.891J)

B. Space system architecture and design

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

C. Space system engineering

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

D. System safety

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