MIT Physics PhD Core Requirements Syllabus

Classical Mechanics:

1. Newton's laws for systems of particles (momentum, energy, center of mass, angular momentum, friction, solutions for motion, relativistic mechanics)
2. Lagrangian and Hamiltonian formulations of mechanics (calculus of variations, Lagrangian and Hamiltonian equations of motion, Legendre transformation)
3. Symmetry and Noether's theorem (cyclic coordinates, conservation laws)
4. Constraints (constraints to surfaces by elimination of variables, use of Lagrange multipliers, generalized forces such as forces of constraint)
5. Orbits and Scattering (motion in a central field, reduced mass, Kepler's problem, Rutherford scattering)
6. Vibrations and Oscillations (normal modes, simultaneous diagonalization of kinetic and potential energy matrices, superposition principle)
7. Canonical transformations (generating functions, Poisson brackets, Liouville's theorem)
8. Rigid body motion (moment of inertia tensor, Euler equations, centrifugal and Coriolis fictitious forces, precession and nutation)
9. Basics of fluid mechanics (continuity equation, ideal fluids, shear viscosity, Euler and Navier-Stokes equations, steady flows, Reynolds number)

References for these topics:

- *Latex lecture notes for 8.309,* by Iain Stewart (covers all topics in suitable depth except for A and E): Stewart-Classical-Mechanics-III
- *Classical Mechanics,* by Goldstein, Poole, Safko (covers all qualifying exam topics except for fluid mechanics)

Other references which may be useful include *Classical Dynamics* by Thornton and Marion (good reference at slightly lower level than Goldstein); *Mechanics* by Symon (good reference for its chapter on perfect fluids); Landau and Lifshitz volume 1 (for general mechanics) and volume 6 (for viscous fluids); Fluid Mechanics by Smits (useful for fluid problems); *Classical Dynamics: a Contemporary Approach* by Jose and Saletan (a relatively mathematical approach that also includes more modern topics and hydrodynamics)

Electromagnetism

1. Basics of EM
    - 1.1 Charges, currents
    - 1.2 Maxwell’s Equations in vacuum
    - 1.3 Scalar and Vector Potentials
    - 1.4 Fields in materials (polarizability, magnetization, macroscopic fields, linear materials, Ohm's law)
    - 1.5 Boundary Conditions at Interfaces
    - 1.6 Electrostatic and magnetostatic limits
    - 1.7 Energy in electric fields and magnetic fields

2. Boundary Value Problems
    - 2.1 Method of images
    - 2.2 Separation of variables: cartesian, spherical, cylindrical coordinates
    - 2.3 Green Function methods
    - 2.4 Multipole methods
    - 2.5 Boundary value problems in materials

3. Waves and wave guides
    - 3.1 Electromagnetic waves in vacuum
    - 3.2 Polarization
    - 3.3 Poynting vector and intensity
    - 3.3 Electromagnetic waves in materials
    - 3.4 Reflection/refraction from an interface
    - 3.5 Propagation in a wave guide

4. Radiation
    - 4.1 Lienard-Wiechert solution of Maxwell's equations in Lorenz gauge
    - 4.2 Far-field and non-relativistic approximations
    - 4.3 Electric and magnetic dipole radiation
    - 4.4 Multipole radiation

5. Scattering and diffraction
    - 5.1 Scattering of EM waves
    - 5.2 Long wavelength
    - 5.3 Short wavelength
    - 5.4 Diffraction (scalar case)

6. Relativistic electrodynamics
    - 6.1 Covariant form of Maxwell's equations
    - 6.2 Lagrangian formulation of the EM field
    - 6.3 Energy-momentum tensor and conservation laws
    - 6.3 Relativistic motion of charged particles in uniform E and B fields

    6.4 Solution of covariant wave equation

7. Radiation by relativistic charges
    7.1 Radiation by an accelerated point charge
    7.2 Thomson scattering
    7.3 Bremsstrahlung, synchrotron radiation

The level here is intermediate between *Introduction to Electrodynamics* by Griffiths and *Classical Electrodynamics* by Jackson. Topics 1), 3), 4), and 6) are mostly Griffiths material, while topics 2), 5), and 7) are mostly Jackson. Other useful sources are *Modern Electrodynamics* by Zangwill, Likharev's notes, volume 2 of the Feynman lectures, and Landau/Lifschitz volume 2.

Statistical Mechanics

1. Microcanonical ensemble, entropy, temperature. Examples from ideal gas, discrete systems (spins, vacancies, etc.)
2. Thermodynamics from statistical mechanics, temperature, heat, work
3. Canonical and grand canonical ensembles; classical ideal gas
4. Kinetic theory of gases (Liouville's theorem, linearized Boltzman equation, H-theorem, approach to equilibrium)
5. Quantum statistics, density matrices, fermions and bosons
6. Ideal gas of non-interacting fermions
7. Ideal gas of non-interacting bosons
8. Phase diagram of an Ising magnet (exact results in one-dimension, mean-field approach in higher dimensions)
9. Phase diagram of water; latent heat
10. Van der Waals equation, critical point, Maxwell construction
11. Random walks, Brownian motion, diffusion, Einstein relation

References:

- *Statistical Physics of Particles,* by Kardar (textbook, videos, and lecture notes)
- *Statistical Mechanics: Entropy, Order Parameters, and Complexity*, by Sethna
- Material for topic 11 is available (videos and notes) on the web-course "Mathematical methods for aspiring physicists," developed by Kardar and Detmold.

Quantum Mechanics

1. Formalism of quantum mechanics:
    1.1. Hilbert space, operators, the measurement postulate
    1.2. The uncertainty principle
    1.3. Pictures: Schrödinger, Heisenberg, Interaction
2. Quantum mechanics of particles in a potential with and without spin
    2.1. Square well potential
    2.2. Quantum harmonic oscillator - via Schrödinger equation as well as algebraically via creation/annihilation operators, coherent and squeezed states
    2.3. Orbital angular momentum
    2.4. Central potentials
    2.5. Hydrogen atom (including fine structure, hyperfine structure and Zeeman effect)
3. Symmetries
    3.1. Continuous symmetries and conservation laws
    3.2. Time and space translations, rotations
    3.3. Spin, representations of SU(2)
    3.4. Time reversal and parity
    3.5. Degeneracies
    3.6. Addition of angular momentum
4. Particle motion under the influence of electromagnetic fields
    4.1. Gauge invariance
    4.2. Landau levels
    4.3. Aharonov-Bohm effect
5. Approximate methods
    6. Variational principle
    7. WKB approximation and the classical limit
    7.1. Time-independent perturbation theory (including degenerate perturbation theory)
    7.2. Time-dependent perturbation theory, Fermi's Golden rule
    7.3. Interaction of atoms with classical EM fields, Einstein A and B coefficients, selection rules
    7.4. Adiabatic approximation, Berry's phase
7.5. Quantum mechanics of identical particles
    7.6. Bosons and fermions,
    7.7. Exclusion principle,
    7.8. Permutation symmetry and symmetrization
    7.9. Exchange interactions
8. Entanglement
    8.1. Density matrices
    8.2. Von Neumann entropy
    8.3. Bell inequality
9. Scattering theory
    9.1. One-dimensional scattering

9.2. Lippmann Schwinger Equation, Born and Eikonal approximations, Optical theorem
9.3. Scattering off of a central potential in three dimensions
9.4. Partial waves decomposition
9.5. Low energy scattering, bound states, resonances

References: The level for these topics should be roughly that of the textbook *Modern Quantum Mechanics* by J. J. Sakurai. The books by Shankar and Cohen-Tannoudji are also recommended as additional resources. Weinberg's book *Lectures on Quantum Mechanics* and volume 3 of Landau/Lifshitz are excellent as well, but are at a somewhat higher level.