Course Structure for
M.Sc. in Mathematics
(Academic Year 2022 – 2024)

School of Physical Sciences
Jawaharlal Nehru University

Contents

1 Preamble

The School of Physical Sciences (SPS) is one of the leading departments in India in terms of research and teaching in physical sciences. The SPS faculty has made significant contributions to novel interdisciplinary areas interfacing physics, chemistry and mathematics. In addition to carrying out research in traditional areas of physics, chemistry and mathematics, the school has developed computing facilities and well-equipped research and teaching laboratories.

Six years ago, during the academic year $2010-2011$, the school initiated a Pre-Ph.D./Ph.D. programme in Mathematics. The M.Sc. programme in Mathematics started during the academic year $2019-2020$, which is a 2 (TWO) years programme consisting of 4 (FOUR) semesters. Each course carries four credits. The courses, together with a compulsory one-semester-long project of four credits, will count to fulfill the minimum of 64 credits for the M.Sc. degree.

1.1 Minimum eligibility criteria for admission

- Candidates should have either one of the following degrees:
    1. Bachelor of Science degree in Mathematics or Bachelor of Arts degree in Mathematics under the $10+2+3/4$ system with at least 55% marks or equivalent.
    2. B. Tech or B. E. (in any of the engineering branches) with at least 6.0 out of 10 CGPA or equivalent.
- For SC/ST and PWD candidates the qualifying degree is relaxed to 50% or 5.5 out of 10 CGPA or equivalent.

1.2 Selection procedure

- The eligible candidates have to appear for the JNU Entrance Examination for M.Sc in Mathematics.
- Candidates will be selected based on the JNU admission policy.

BACK TO THE TABLE OF CONTENTS

2 Programme structure

2.1 Overview

- 12 Core courses + 1 Project + 3 Electives for a total of 16 courses.
- A project is a compulsory course.
- Each course carries 4 credits for a total of 64 credits.

2.2 Semester wise course distribution

Semester I	**Semester II**	**Semester III**	**Semester IV**
Algebra I	Algebra II	Elective I	Partial Differential Equations
Discrete Mathematics	Measure Theory	Computational Mathematics	Probability and Statistics
Real Analysis	Functional Analysis	Ordinary Differential Equations	Elective II
Basic Topology	Complex Analysis	Project	Elective III

BACK TO THE TABLE OF CONTENTS

3 Courses: core and elective

Core Courses		
Sl. No.	**Course Name**	**Course Code**
1.	Algebra I	PM401
2.	Complex Analysis	PM402
3.	Real Analysis	PM403
4.	Basic Topology	PM404
5.	Algebra II	PM405
6.	Measure Theory	PM406
7.	Functional Analysis	PM407
8.	Discrete Mathematics	PM408
9.	Probability and Statistics	PM409
10.	Computational Mathematics	PM410
11.	Ordinary Differential Equations	PM411
12.	Partial Differential Equations	PM412
13.	Project	PM413
Elective Courses		
Sl. No.	Course Name	Course Code
1.	Number Theory	PM501
2.	Differential Topology	PM502
3.	Harmonic Analysis	PM503
4.	Analytic Number Theory	PM504
5.	Proofs	PM505
6.	Advanced Algebra	PM506
7.	Algebraic Topology	PM507
8.	Banach and Operator Algebras	PM508
9.	Numerical Analysis	PM509
10.	Computational Fluid Dynamics	PM510

BACK TO THE TABLE OF CONTENTS

4 Details of the core courses

4.1 Algebra I (PM401)

Prerequisites: Basic Group Theory, Basic Linear Algebra

1. **A quick review of Group Theory:** Examples - dihedral, symmetric, permutation, quaternions and some matrix groups, such as $\mathrm{GL}_n, \mathrm{SL}_n$, Abelian and cyclic groups, subgroups, normal subgroups, Centralizer and normalizer of a group. Lagrange's theorem and isomorphism theorems. Group actions, class equation, counting orbits, Cayley's theorem, Sylow's theorems, simplicity of alternating groups.

2. **Construction of groups and classification results:** Direct product, classification of finitely generated abelian groups (statement without proof), semi-direct product, classification of groups of small order (up to 15), wreath product, free groups, examples of presentations of groups

3. **Composition series, solvable groups, nilpotent groups**.

4. **A quick review of Linear Algebra:** Vector spaces, linear independence, bases, linear transformations, rank-nullity theorem, dual space, double dual, eigenvectors, eigenvalues, characteristic polynomial and minimal polynomial, Cayley-Hamilton Theorem.

5. **Canonical forms:** Diagonalizability and diagonalization, primary decomposition theorem, generalized eigenvectors, Jordan canonical form (statement), rational canonical form (statement)

6. **Inner product spaces:** Orthonormal bases, Gram-Schmidt process, linear functionals and adjoints, Hermitian, unitary and normal operators, symmetric and skew symmetric bilinear forms, groups preserving bilinear forms.

7. **Additional Topics:** Action of linear groups on $\mathbb{R}^n$, rigid motions, $\mathrm{SO}(3, \mathbb{R})$ and Euler's theorem, definition of representation of a group with examples, tensor product of vectors spaces

Main Text Books:

1. D. S. Dummit and R. M. Foote, Abstract Algebra, Third edition, Wiley India, 2011

2. I. N. Herstein, Topics in Algebra, Second edition, John Wiley and sons, 2000

3. J. Rotman, An introduction to the theory of groups, Fourth edition, Graduate Texts in Mathematics, 148, Springer-Verlag, New York, 1995

Supplementary References:

1. M. Artin, Algebra, Prentice Hall, Inc., Englewood Cliffs, NJ, 1991

2. T. W. Hungerford, Reprint of the 1974 original, Graduate Texts in Mathematics, 73, Springer-Verlag, New York-Berlin, 1980

3. S. H. Friedberg, A. J. Insel, and L. E. Spence, Linear algebra, Third edition, Prentice Hall, Inc., 1997

4. S. Lang, Algebra, Revised third edition, Graduate Texts in Mathematics, 211, Springer-Verlag, New York, 2002

5. N. Jacobson, Basic Algebra Vol. I and II, Second edition, W. H. Freeman and Company 1989

6. N.S Gopalkrishnan, University Algebra, Second edition, New Age International, New Delhi, 1986

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

4.2 Complex Analysis (PM402)

Prerequisites: Basic knowledge of Real Analysis

1. **Quick Review of Complex numbers:** Basic operations, conjugate, modulus, argument, exponential function, roots
2. **Holomorphic functions:** Continuity, derivative, holomorphic functions, Cauchy-Riemann differential equations, harmonic functions
3. **Elementary functions:** Polynomial and rational functions, exponential function, logarithm, trigonometric and hyperbolic functions
4. **Complex integration:** Paths and contours, integration, estimation theorem, Cauchy's integral formula, Cauchy's theorem, Liouville's theorem, fundamental theorem of algebra, maximum modulus principle, Schwarz's lemma
5. **Series:** (absolute and uniform) Convergence of series, power series, Taylor series, Laurent series, the identity principle
6. **Zeros, singularities and residues:** Classification of singularities, orders of poles and zeros, winding number, meromorphic functions, Cauchy's residue theorem, argument principle
7. **Mappings:** Linear fractional transformations, conformal mappings
8. **Application of complex integration:** Computation of indefinite integrals
9. **Additional Topics:** Branch points, doubly periodic functions, construction of sine, cosine as an inverse of a multi-valued function, Riemann mapping theorem, Dirichlet problem, analytic continuation, multivariable complex analysis

Main Text Book:

1. L. V. Ahlfors, Complex analysis, An introduction to the theory of analytic functions of one complex variable, Third edition, International Series in Pure and Applied Mathematics, McGraw-Hill Book Co., New York, 1978
2. J. B. Conway, Functions of one complex variable, Graduate Texts in Mathematics 159, Springer-Verlag, New York, 1995

Supplementary References:

1. W. Rudin, Real and complex analysis, Third edition, McGraw-Hill Book Co., New York, 1987
2. E.M. Stein, R. Sharkarchi, Complex analysis, Princeton Lectures in Analysis, 2, Princeton University Press, Princeton, NJ, 2003
3. E. Goursat, A Course in Mathematical Analysis, Functions of a complex variable, Part I of Vol. II, Ginn and Company, 1916

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

4.3 Real Analysis (PM403)

Prerequisites: Basic knowledge of Real Analysis and Linear Algebra

1. **Quick review of basic Real Analysis:** Construction of real numbers, order on real numbers and the least upper bound property, convergence of sequence and series, power series, multiplication of series, absolute and conditional convergence, rearragements (with proof of Riemann's Theorem). Continuity, uniform continuity, compactness and connectedness in metric spaces. Differentiation: L'Hospital's rule, derivatives of higher orders, Taylor's theorem, differentiation of vector-valued functions

2. **The Riemann-Stieltjes Integral:** Definition and existence of the integral, properties of the integral, integration and differentiation, integration of vector-valued functions, rectifiable curves

3. **Sequences and Series of Functions:** Pointwise and uniform convergence, uniform convergence and continuity, uniform convergence and integration, uniform convergence and differentiation, equicontinuity, Arzela-Ascoli theorem, Stone-Weierstrass theorem

4. **Calculus of Several Variables:** Differentiation of functions of several real variables (directional derivatives, partial derivatives, differentiability and the total derivative, chain rule, Jacobian, higher derivatives, interchange of the order of differentiation, Taylor's theorem), inverse function theorem, implicit function theorem, rank theorem, differentiation of integrals, derivatives of higher order

5. **Additional Topics:** Integration of differential forms: Integration, primitive mappings, partition of unity, change of variables, differential forms, Stokes' theorem, closed and exact forms. Some special functions: Power series, exponential and logarithmic functions, trigonometric functions, Gamma function, Fourier series

Main text book:

1. W. Rudin, Principles of Mathematical Analysis, Third edition, McGraw Hill Book Company, New York, 1976

Supplementary References:

1. T. M. Apostol, Mathematical Analysis, 2nd edition, Addison-Wesley Publishing Company, Reading, Massachusetts, 1974

2. T. Tao, Analysis I and II, Third editions, Texts and Readings in Mathematics, Hindustan Book Agency, New Delhi, 2006

3. M. Spivak, Calculus on Manifolds: A modern approach to classical theorems of advanced Calculus, West View Press, 27^{th} printing, 1998

4. K. Jänich, Vector Analysis, Undergraduate Texts in Mathematics, Springer, 2001

5. S. Lang, Undergraduate Analysis, Second edition, Springer, 2005

6. H. L. Royden and P. M. Fitzpatrick, Real Analysis, Fourth Edition, Pearson Education, Inc., 2010

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

4.4 Basic Topology (PM404)

Prerequisites: Basic knowledge of Real Analysis and Metric Spaces

1. **Familiarity with Set Theory:** Countable and uncountable sets, axiom of choice and its variants.
2. **Topological Spaces and continuous functions:** Topology, basis, sub-basis, Hausdorff and regular spaces, order topology, subspace topology, limit points, continuous functions, homeomorphisms, product topology and metric topology.
3. **Quotient Topology:** Quotient map, quotient topology, quotient space.
4. **Nets:** Subnets, convergence of nets
5. **Connectedness and Compactness:** Connectedness, path-connectedness, compactness, comparison with compactness in metric spaces via nets, local compactness and one-point compactification
6. **Countability and Separation Axioms:** First and second countability, separability, normality, complete regularity, Urysohn's lemma, Tietze extension theorem, Tychonoff theorem and Stone-Cěch compactification
7. **Additional Topics:** Urysohn Metrization theorem, local finiteness, Nagata-Smirnov metrization theorem, paracompactness and Smirnov metrization theorem

Main Text Books:

1. J. R. Munkres, Topology, Second Edition, Pearson, 2000
2. G. E. Bredon, Topology and Geometry, Graduate Texts in Mathematics, 139, Springer, 1993

Supplementary References:

1. C. O. Christenson and W. L. Voxman, Aspects of Topology, Second edition, B. C. S. Associates, 1998
2. K. Jänich, Topology, Undergraduate Text in Mathematics, Springer, 1984
3. J. L. Kelley, General Topology, Graduate Text in Mathematics, Springer, 1975
4. G. F. Simmons, Topology and Modern Analysis, Tata McGraw-Hill, 2004
5. J. Dugundji, Topology, McGraw-Hill Inc., 1988

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

4.5 Algebra II (PM405)

Prerequisites: Basic knowledge of Ring Theory, Algebra I

1. **Review of the theory of rings:** Rings and subrings, homomorphisms, ideals, prime ideal, maximal ideal, quotient ring, examples of rings - matrix ring, division ring, polynomial rings,

2. **Further topics on rings:** Radical of an ideal, nilradical, Jacobson radical, Chinese remainder theorem, Euclidean domain, principal ideal domain, unique factorization domain, Gauss's lemma, irreducibility criteria

3. **Modules:** Definition and examples, short exact sequences, free modules, torsion sub-modules, tensor product of modules. Structure of finitely generated modules over a PID

4. **Field theory:** Definition and examples, extension of fields, finite and infinite extensions, algebraic and transcendental extensions. Homomorphism, isomorphism, automorphism. Separable extensions, normal extensions. Splitting field of a polynomial. Extending field morphisms. Existence and uniqueness (up to isomorphism) of algebraic closure of a field. Finite fields, cyclicity of multiplicative group of a finite field

5. **Galois Theory:** Introduction to Galois Theory, examples of Galois groups, fundamental theorem of Galois theory

6. **Additional Topics:** Direct limit, inverse limit of modules. Constructions using a straight edge and a compass. Solvability of equations using the radicals

Main Text Books:

1. D.S. Dummit and R.M. Foote, Abstract Algebra, Third edition, Wiley India, 2011

2. I. N. Herstein, Topics in Algebra, Second edition, John Wiley and sons, 2000

3. M. Artin, Algebra, Prentice Hall, Inc., Englewood Cliffs, NJ, 1991

Supplementary References:

1. S. Lang, Algebra, Graduate Texts in Mathematics 211, revised third edition, Springer-Verlag, New York, 2002

2. E. Artin, Edited and supplemented with a section on applications by Arthur N. Milgram, Second edition, with additions and revisions, Fifth reprinting, Notre Dame Mathematical Lectures, No. 2, University of Notre Dame Press, South Bend, Ind. 1959

3. N.S Gopalkrishnan, University Algebra, Second edition, New Age International, New Delhi, 1986

4. N.S Gopalkrishnan, Commutative Algebra, Oxonian Press Pvt. Ltd., New Delhi, 1984

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

4.6 Measure Theory (PM406)

Prerequisites: Real Analysis, Basic Topology

1. **Quick review of Riemann Integration**
2. **Lebesgue Measure on $\mathbb{R}$:** Outer measure, outer regularity of outer measure, Lebesgue measure, regularity of Lebesgue measure, non-measurable sets
3. **Lebesgue Integral:** Simple functions, almost everywhere property, measurable functions, integrable functions, approximation of integrable functions by step and continuous functions
4. **Convergence of sequence of functions:** Pointwise, uniform, Egorov's theorem, Lusin's theorem
5. **Abstract measure spaces:** Sigma algebras and measurable spaces, measures and measure spaces, completeness of a measure, measurable functions and their integration, monotone convergence theorem, Fatou's lemma, dominated convergence theorem, modes of convergence
6. **Product measure:** product sigma algebra, sigma-finite measure spaces, existence of product measures, Tonelli's theorem, Fubini's theorem
7. **Additional Topics:** Lebesgue differentiation theorem, almost everywhere differentiability, absolute continuity Caratheodory's Extension theorem for outer measures, Hahn-Kolmogorov extension theorem for pre-measures, Lebesgue-Stieltjes measure, Radon measure

Main Text book:

1. T. Tao, An Introduction to Measure Theory, GTM 126, American Mathematical Society, 2011

Supplementary References:

1. G. B. Folland, Real Analysis: Modern Techniques and their Applications, expanded and revised edition, John Wiley and Sons, 2013
2. W. Rudin, Real and Complex Analysis, Third Edition, McGraw-Hill, 1987

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

4.7 Functional Analysis (PM407)

Prerequisites: Real Analysis, Basic Topology

1. **Hilbert spaces:** Inner product spaces, Hilbert spaces, orthogonality, Riesz representation Theorem, orthonormal sets, orthogonalization, unconditional sum, orthonormal bases, isomorphisms of Hilbert spaces, separable Hilbert spaces, direct sums of Hilbert spaces
2. **Operators on Hilbert spaces:** Examples, adjoint of an operator, invertible operators, self-adjoint operators, unitary operators, isometries, projections, compact operators
3. **Banach Spaces:** Normed spaces, equivalence of norms, some inequalities, Banach spaces, finite dimensional spaces, quotient and products of normed spaces, bounded linear operators and functionals
4. **Dual Spaces:** Hahn-Banach theorem, dual of a quotient space and a subspace, reflexive spaces
5. **Category Theorems:** Baire category theorem, open mapping theorem, closed graph theorem, principle of uniform boundedness
6. **Operators on Banach spaces:** Adjoint of an operator, annihilators, compact operators
7. **Additional Topics:** Weak topology, weak-* topology, Banach-Alaoglu theorem, Goldstine's theorem, reflexivity in terms of weak topology, separable Banach spaces

Main Text Books:

1. John B. Conway, A Course in Functional Analysis, Graduate Texts in Mathematics 96, Second edition 1990, corrected fourth printing, Springer, 1994
2. S. Kesavan, Functional Analysis, Texts and Readings in Mathematics (TRIM series), 52 Corrected reprint, Hindustan Publishing Agency, 2017

Supplementary References:

1. G. F. Simmons, Introduction to Topology and Modern Analysis, Tata McGraw-Hill, 2004
2. W. Rudin, Real and Complex Analysis, Third Edition, McGraw-Hill,1987
3. W. Rudin, Functional Analysis, McGraw-Hill Education, Third Edition, 1986
4. G. K. Paderson, Analysis Now, Graduate Texts in Mathematics 118, Springer 2012
5. H. L. Royden and P. M. Fitzpatrick, Real Analysis, Fourth Edition, Pearson Education, Inc., 2010

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

4.8 Discrete Mathematics (PM408)

Prerequisites: Algebra I

1. **Set theory and logic:** Basic concepts, cardinal numbers
2. **Counting:** Mathematical induction, pigeonhole principle, permutations and combinations, inclusion-exclusion principle, recurrence relations, generating functions, Polya's theorem
3. **Graph theory:** Basic definitions, trees and distance, matchings, connectivity, graph colourings, Ramsey theory, planar graphs
4. **Cryptography:** Public key cryptography, RSA, discrete log problem
5. **Additional Topics:** Codes and encoding, error detection and correction, linear codes, cyclic codes

Main Text Book:

1. M. Aigner, Discrete Mathematics, Translated from the 2004 German original by David Kramer, American Mathematical Society, Providence, RI, 2007

Supplementary References:

1. K. Rosen, Discrete Mathematics and its applications, McGraw-Hill Book Co., New York,2012
2. P. R. Halmos, Naive set theory, Reprint of the 1960 edition, Undergraduate Texts in Mathematics. Springer-Verlag, New York-Heidelberg, 1974
3. R. L. Graham, D. E. Knuth, O. Patashnik, Concrete mathematics, A foundation for computer science, Second edition, Addison-Wesley Publishing Company, Reading, MA, 1994
4. R. Diestel, Graph theory, Fourth edition, Graduate Texts in Mathematics, 173, Springer, Heidelberg, 2010

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

4.9 Probability and Statistics (PM409)

Prerequisites: Real Analysis, basic knowledge of combinatorics

1. **Probability and random variables:** Repeated experiments and empirical definition of probability. Sample space, events. Probability as a set function on a σ-algebra. Random variables, distribution functions and probability density functions. Expectation value, variance and higher moments. Moment generating functions, inequalities of Markov and Chebyshev.

2. **Conditional probability and independence:** Conditional probability, marginal distributions and conditional distributions. Covariance and correlation, stochastic independence.

3. **Some probability distributions:** Binomial, Poisson and normal distributions. Properties of their moments.

4. **Distributions of functions of random variables:** Sampling. Transformations of random variables, Student's t and F distributions. Distributions of mean and variance of a sample. Expectations of functions of random variables.

5. **Limiting distributions:** Stochastic convergence of random variables. Weak and strong laws of large numbers (without proofs). Central limit theorem.

6. **Additional topics:** Hypothesis testing - Examples and definitions. Uniformly most powerful tests. Likelihood ratio tests. Statistical significance.

Main Text Books:

1. R. V. Hogg and A. T. Craig, Introduction to Mathematical Statistics, Fourth edition, McMillan Publishing Company, 1978

2. S. Ross, A First Course in Probability, 8th Edition, Prentice Hall/Pearson, 2010

Supplementary References:

1. W. Feller, An Introduction to Probability Theory and Its Applications, Vol. I, Third edition, Wiley, 2008

2. W. Feller, An Introduction to Probability Theory and Its Applications, Vol. II, Second edition, Wiley, 2008

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

4.10 Computational Mathematics (PM410)

Prerequisites: Algebra I, Real Analysis, Complex Analysis, Linear Algebra, additionally some knowledge of elementary number theory and ODEs will help, but is not essential.

Goal: The aim is to introduce the students to algorithmic way of learning, to teach them the importance of computations and to the use of computers for implementation of a few algorithms. We will be using a few programming tools such as C++, MATLAB/SciLab, SAGE to implement a few well-known algorithms from Calculus, Number Theory, Linear Algebra, Algebra, Graph Theory, Discrete Mathematics and possibly Differential Equations and Statistics depending on the preparation and inclination of the students.

This course will have a practical component and labwork.

1. **Algorithms:** Introduction to algorithms with a few standard examples
2. **Brief Introduction to Programming:** Introduction to programming languages and computational systems such as C++, SAGE, MATLAB/SciLab
3. **Algorithms in Calculus:** Newton-Raphson iteration method for finding real root, numerical integration
4. **Algorithms in Linear Algebra:** Solving systems of linear equations, diagonalization
5. **Algorithms in Differential Equations:** Solution of ordinary differential equations, Runge-Kutta
6. **Algorithms in Number theory:** Sieve of Eratosthenes, primality tests, Euclidean algorithm, greatest common divisor, solution to Pell's equation using continued fractions
7. **Algorithms in Graph Theory and Discrete Mathematics:** Kruskal's algorithm, finding Eulerian cycles, sorting and searching algorithms
8. **Additional topics:** Computation of Galois groups, Gröbner bases

Main References:

1. Thomas H. Cormen, Charles E. Leiserson, Ronald L. Rivest, Clifford Stein, Introduction to Algorithms, Third edition, MIT Press, 2009
2. S. Pemmaraju and S. Skiena, Computational Discrete Mathematics, First Reissue edition, Cambridge University Press, 2009
3. Henry Cohen, A Course in Computational Algebraic Number Theory, Springer, 1993
4. SAGE http://www.sagemath.org/, open-source mathematics software system

Supplementary References:

1. D. F. Holt, B. Eick, E. A. O'Brien, Handbook of Computational Group Theory, Chapman and Hall/CRC Press 2005

2. F. Villegas, Experimental Number Theory, Oxford Graduate Texts in Mathematics, Book 13, 2007
3. D. E. Knuth, The Art of Computer Programming Volumes 1 to 4, Addison-Wesley Professional, First edition, 2011
4. M. Petkovsek, H. Wilf and D. Zeilberger, A = B, A. K. Peters/CRC Press, 1996

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

4.11 Ordinary Differential Equations (PM411)

Prerequisites: Calculus, Linear Algebra, Real Analysis

1. **Quick Review of some basic methods of solving first order ODEs :** Motivation, Order and degree of ODEs. Method of separation of variables. Exact Differential Equations. Integrating Factors.

2. **Existence, Uniqueness and Continuity Theorems for first order ODEs :** Picard's existence and uniqueness Theorem, Picard's successive approximation method, Continuity of solutions with respect to initial conditions, Gronwal's inequality.

3. **Second order linear ODEs :** Vector space of space of solutions. Wronskian and linear independence of solutions. Linear ODE with constant coeffecients. Variation of parameters. Method of undetermined coefficients. Sturm Separation Theorem. Sturm Comparison Theorem.

4. **Solution in series of second order ODEs :** Ordinary and singular points. Power series solution at an ordinary point. Legendre's equation. Solutions at a regular singular point using the Frobenius method. Bessel's equation.

5. **Systems of first order ODEs :** System of first order ODEs versus n-th order ODE. Existence and uniqueness Theorem for system of first order ODEs. Existence and uniqueness Theorem for n-th order ODEs. Picard's succesive approximation method. Homogeneous linear systems of first order ODEs. Fundamental matrix and solution matrix. Nonhomogeneous linear systems. Linear systems with constant coefficients.

6. **Boundary-value problems and self-adjoint eigenvalue problems :** Two point boundary value problems, Green's functions. Sturm-Liouville systems. Eigenvalues and eigenfunctions.

7. **Additional topics :**
(a) Stability Analysis : Linear systems, Stability for linear systems with constant coefficients, Stability of linear plane systems
(b) Laplace transform : Properties of the Laplace transform, Convolution Theorem, Step function, Impulse function.
(c) Cauchy-Peano Existence Theorem: Arzela-Ascoli Theorem. Existence of solution of ODEs not satisfying the Lipshitz condition.

Suggested texts:

1. Coddington, E., An Introduction to Ordinary Differential Equations, Dover Publications, 2012 (Original: Prentice-Hall, 1961)

2. Coddington, E., and Levinson N., Theory of Ordinary Differential Equations, Tata-McGraw-Hill, 1990

3. Myint-U, T., Ordinary Differential Equations, North-Holland, New York, 1978

4. Rabenstein, A. L., Introduction to Ordinary Differential Equations, Elsevier Science, 2014

5. Ross, S. L., Introduction of Ordinary Differential Equations, 4 th Ed., John Wiley and Sons, 2007

6. Simmons, G. F., Differential Equations with Applications and Historical Notes, CRC Press, 2017

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

4.12 Partial Differential Equations (PM412)

Prerequisites: Calculus, Linear Algebra, Complex Analysis, Ordinary Differential Equations

1. **Motivation:** PDE in natural science. First order PDE, examples.
2. **Second order PDE:** Classification and reduction to canonical forms. Well-posed problem. Characteristics. Green's function.
3. **Laplace equation (elliptic):** Boundary value problem, Dirichlet and Neumann boundary conditions. Harmonic functions. Mean value theorem. Solution by separation of variables.
4. **Heat equation (parabolic):** Initial and boundary value problem. Solution by separation of variables. Duhamel's principle.
5. **Wave equation (hyperbolic):** D'Alembert's solution. Cauchy problem, existence and uniqueness of solutions. Solution by separation of variables.
6. **Additional topics:** Fourier transform method. Laplace and Mellin transforms.

Main Text Books:

1. I. Sneddon, Elements of Partial Differential Equations, Dover reprint, Dover, 2006

Supplementary References:

1. L. C. Evans, Partial Differential Equations, Second edition, American Mathematical Society, 2010
2. J. Fritz, Partial Differential Equations, Fourth edition, Springer, 1991
3. E. L. Ince, Ordinary Differential Equations, reprint edition, Dover 1956
4. V. I. Arnold, Lectures on Partial Differential Equations, Third edition, Springer, 2006
5. T. Amaranath, An Elementary Course in Partial Differential Equations, Second edition, Narosa, 2014

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

4.13 Project (PM413)

Prerequisites: Reasonably good understanding about M.Sc. first year courses; especially those related to the project topic

Goal: The project is of one semester duration and carries 4 credits. A student will choose a topic (either a research paper or some other advanced material related to but beyond the first year courses). The student will then learn the material under the supervision of a teacher. It is expected that the student will meet the supervisor regularly (at least once per week) and present the material that he/she has learnt and keep his/her supervisor updated with his/her progress. The student is also expected to write an expository essay of about 10 to 15 pages on the project topic and also present it to a panel of examiners at the end of the term.

Grading scheme: The student's performance will be evaluated based on the presentations (working seminars to the supervisor), project essay and final presentation and the grading scheme for this course will be announced prior to the beginning of the project course.

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

5 Details of the elective courses

5.1 Number Theory (PM501)

Prerequisites: Algebra I, Algebra II, Real Analysis, Complex Analysis

Goal: To provide an introduction to Number Theory that is beyond an undergraduate elementary number theory course and having algebraic, algebraic geometric and also analytic components. This course will cover a few topics which will illustrate that number theory uses tools from all the various disciplines of mathematics.

1. **Unique factorization and applications:** $\mathbb{Z}, k[x]$, unique factorization in a principal ideal domain, study of $\mathbb{Z}[i], \mathbb{Z}[\omega]$ and $\mathbb{Z}[\frac{1+\sqrt{-5}}{2}]$
2. Congruences, structure of $(\mathbb{Z}/n\mathbb{Z})^*$
3. Quadratic reciprocity, Gauss and Jacobi Sums
4. Equations over finite fields, Hasse-Davenport relation, zeta function as a generating function of number of solutions
5. Riemann zeta function. Definition of Dirichlet L-functions attached to a character with the possibility of deeper study of L-function attached to a character of order 2
6. Diophantine equations of genus 0 over the rationals: Pythagorean triplets, Pell's equation
7. Irrationality and transcendence of e and π
8. **Additional Topics:** Brief introduction to algebraic number theory, a very brief introduction to elliptic curves, the group law on an elliptic curve possibly without proof of the associativity property, a few important concrete examples and computations, connection to congruence number problem and Fermat's last theorem

Main Text Book:

1. K. Ireland and M. Rosen, A Classical Introduction to Modern Number Theory, Graduate Texts in Mathematics 84, Springer-Verlag, 1990

Supplementary References:

1. G. H. Hardy and E. M. Wright, An Introduction to the Theory of Numbers, Sixth Edition (edited by R. Heath-Brown, J. Silverman, and A. Wiles), Oxford University Press, 2008
2. I. Niven, H. S. Zuckerman, H. L. Montgomery, An Introduction to the Theory of Numbers, Fifth Edition, John Wiley and sons, Inc., 1991
3. N. Koblitz, Introduction to elliptic curves and modular forms, Graduate Texts in Mathematics, second edition, Springer, 1993

4. J. Silverman, The Arithmetic of Elliptic Curves, Graduate Texts in Mathematics 106, second edition, Springer-Verlag New York, 2009
5. J. Silverman and J. Tate, Rational points on elliptic curves, Undergraduate Texts in Mathematics, Second edition, Springer International Publishing, 2015
6. J.-P. Serre, A course in Arithmetic, Graduate Texts in Mathematics 7, Springer-Verlag New York, 1973
7. F. Villegas, Experimental Number Theory, Oxford Graduate Texts in Mathematics, Book 13, 2007

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

5.2 Differential Topology (PM502)

Prerequisites: Linear Algebra, Topology, Real Analysis

1. **Quick review of multivariable calculus:** Implicit and inverse function theorems
2. **Quick review of separation axioms and paracompactness:** First and second countability, separability, normality, complete regularity, Urysohn lemma and paracompactness
3. **Topological manifolds:** Definition and some basic properties
4. **Smooth manifolds:** Smooth atlas, smooth structure, smooth manifolds
5. **Smooth maps:** Smooth maps, diffeomorphisms, bump functions, partitions of unity
6. **Tangent space and the differential:** Derivations, tangent space, tangent vectors to curves, differential of a smooth map
7. **Vector fields:** Tangent bundle, vector fields on manifolds, orientation on a manifold
8. **Immersions, submersions and embeddings:** Implicit and inverse function theorem for manifolds, submersions, immersions
9. **Submanifolds:** Embedded submanifolds and their tangent spaces, regular and critical points and values, level sets, immersed submanifolds
10. **Additional Topics:** Smooth manifolds with boundary and associated definitions, , submanifolds of manifolds with boundary, embedded submanifolds and their tangent spaces, Lie brackets, Sard's theorem, differential forms and integration on manifolds, Stokes' theorem

Main Text Books:

1. J. M. Lee, Introduction to Smooth Manifolds, GTM, Springer, 2006
2. K. Janich, Vector Analysis, Undergraduate Texts in Mathematics, Springer, 2001

Supplementary References:

1. M. Spivak, Calculus on Manifolds: A modern approach to classical theorems of advanced Calculus, West View Press, 27^{th} printing, 1998
2. V. Guillemin and A. Pollack, Differential Topology, AMS Chelsea Publishing, 1974
3. F. W. Warner, Foundations of Differential Manifolds and Lie Groups, Graduate Texts in Mathematics 94 , First edition, Springer, 1983
4. W. Rudin, Principles of Mathematical Analysis, Third edition, McGraw Hill Book Company, New York, 1976
5. G. E. Bredon, Topology and Geometry, Graduate Texts in Mathematics, 139, Springer, 1993
6. A. A. Kosinski, Differential Manifolds, Dover Publications Inc., 2007
7. J. R. Munkres, Elementary Differential Topology, Revised Edition, Annals of Mathematics Studies (AM-54), Princeton University Press, 1967

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

5.3 Harmonic Analysis (PM503)

Prerequisites: Real Analysis, Complex Analysis, Measure Theory

1. **Fourier series:** Fourier development of periodic functions, examples, Dirichlet and Fejer kernels, convergence of Fourier series, Gibb's phenomenon, Parseval's equation
2. **Review of measure theory and integration:** Lebesgue measure, Lebesgue integral, L^p space
3. **Fourier transform:** Motivation and definition, examples, Fourier inversion formula, uniform continuity and Riemann-Lebesgue lemma, Plancherel's theorem, Poisson summation formula, convolution theorem, differentiation of Fourier transforms, Hermite functions, Laplace transform
4. **Applications:** Filtering, differential equations, central limit theorem
5. **Additional Topics:** Spherical harmonic analysis, harmonic analysis on topological groups, Pontryagin duality

Main Text Book:

1. E.M. Stein and G. Weiss, Introduction to Fourier analysis on Euclidean spaces, Princeton Mathematical Series, No. 32, Princeton University Press, Princeton, N.J., 1971

Supplementary References:

1. Y. Katznelson, An introduction to harmonic analysis, Third edition, Cambridge Mathematical Library, Cambridge University Press, Cambridge, 2004
2. G. B. Folland, Fourier analysis and its applications. The Wadsworth and Brooks/Cole Mathematics Series, Wadsworth and Brooks/Cole Advanced Books and Software, 1992
3. L. Grafakos, Classical Fourier analysis, Third edition, Graduate Texts in Mathematics, 249, Springer, New York, 2014

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

5.4 Analytic Number Theory (PM504)

Prerequisites: Complex Analysis

1. **Arithmetic functions and Dirichlet series:** The ring of arithmetic functions, Dirichlet series, important arithmetic functions, average estimates
2. **Characters:** Group characters, Dirichlet characters, detection of residue classes, Gauss sums
3. **Prime number distribution:** Infinitude of primes, Chebyshev's bounds, Riemann zeta function, Perron's formula, prime number theorem, Dirichlet L-functions, primes in arithmetic progressions
4. **Circle method:** General set up, ternary Goldbach problem, partitions
5. **Sieve methods:** Selberg's sieve, large sieve, estimates for twin primes, estimates for twins of almost-primes
6. **Additional Topics:** Modular forms, exponential sums

Main Text Book:

1. T.M. Apostol, Introduction to Analytic Number Theory, Undergraduate Texts in Mathematics. Springer-Verlag, New York-Heidelberg, 1976

Supplementary References:

1. H. L. Montgomery, R.C. Vaughan, , Multiplicative number theory I - Classical theory, Cambridge Studies in Advanced Mathematics, 97, Cambridge University Press, Cambridge, 2007
2. H. Davenport, Multiplicative number theory, Third edition, Revised and with a preface by H. L. Montgomery, Graduate Texts in Mathematics, 74, Springer-Verlag, New York, 2000
3. R. C. Vaughan, The Hardy-Littlewood method, Cambridge University Press 1997
4. A. C. Cojocaru, M. R. Murty, An introduction to sieve methods and their applications, London Mathematical Society Student Texts, 66, Cambridge University Press, Cambridge, 2006
5. S. W. Graham, G. Kolesnik, van der Corput's method of exponential sums, London Mathematical Society Lecture Note Series, 126, Cambridge University Press, Cambridge, 1991
6. N. Koblitz, Introduction to elliptic curves and modular forms, Second edition, Graduate Texts in Mathematics, 97, Springer-Verlag, New York, 1993

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

5.5 Proofs (PM505)

Pre-requisites: Algebra I, Real Analysis, Complex Analysis, Basic Topology

Goal: To discuss the concept of a proof or what would constitute as a piece of an evidence. To introduce, explain and discuss proofs in mathematics, computer science and other disciplines, brief discussion about kinds of proofs using examples, The concept/definition of zero knowledge proof in computer science, computer assisted proofs, formal proof. Another important goal of this course will be to teach the students how to write mathematics and proofs (using examples and possibly small projects as assignments).

1. **What is a proof or a piece of evidence:** Proofs in different walks of life - in politics, in social sciences, in history, as per the judiciary, criminology, in biology, medical sciences, weather prediction, in physics and in mathematics - illustrated using examples in brief.

2. **Proofs in mathematics:**
    - Language of proofs. Introduction to logic
    - Methods of proving: Numerical, computational, by induction (various kinds), by contradiction (reductio ad absurdum), contrapositive, types of proofs - direct, indirect, constructive, non-constructive.
    - How to disprove: how to construct counterexamples?

3. **Proofs in computer science:** The concept of zero-knowledge proof in brief using couple of the following or similar examples (a) Using the game called "where is Waldo"? (b) Graph colouring problem and it's solution by Wigderson et al (c) "How to explain zero knowledge protocols to your children". The concept of a proof certificate - e.g. Pratt's certificate that certifies that a specific large number is a prime number (based on Lucas's theorem). Size and complexity of a proof.

4. **Computer Assisted Proofs:** One or two examples from the below will be discussed in brief: four colour theorem, classification of finite groups, sphere packing, existence of Lorentz attractor

5. **Additional Topics:** Role of proofs in mathematics: Discussions around the main points of the bulletin of AMS article of W. Thurston, errors in mathematical research papers, role of speculation, conjectures, and questions in the progress of mathematics. Concept of a formal proof

Main References:

1. S. Krantz, The proof is in the pudding - The changing nature of mathematical proof, Springer-Verlag, 2011

2. Franklin and Daoud, Proofs in Mathematics - An Introduction, Quakers Hill Press, 1996/Kew Books, 2011

3. M. Aigner and G. Ziegler, Proofs from THE BOOK, Forth edition, Springer-Verlag, 2009

4. M. Petkovsek, H. Wilf and D. Zeilberger, A = B, A K Peters/CRC Press, 1996

5. T. C. Hales, Formal proof, Notices of the AMS, Vol 55, Number 11, 1370−1380 (and references therein)

6. L. Lamport, How to Write a 21st century proof, J. Fixed Point Theory App. Vol. 11, Issue 1 (2012), pp 43 − 63

7. B. Mazur, The faces of evidence (in Mathematics), Notes for the presentation and discussion at Museion, February 5, 2014

Supplementary References:

1. A. Jaffe and F. Quinn, "Theoretical Mathematics": Toward a cultural synthesis of mathematics and theoretical physics, Bulletin of the AMS, Vol. 29, No. 1, July 1993, Pages 1 − 13

2. W. Thurston, On proof and progress in Mathematics, Bull. of the AMS, 30 (1994), 161 − 177

3. T. C. Hales, Jordan's proof of the Jordan Curve Theorem, STUDIES IN LOGIC, GRAMMAR AND RHETORIC 10 (23), 2007

4. B. Mazur, Announcement of a joint undergraduate course (Law, Harvard) taught by Noah Feldman and co-taught by B. Mazur: "Nature of Evidence"

5. B. Mazur, Shadows of Evidence - An essay on science, 2013

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

5.6 Advanced Algebra (PM506)

Prerequisites: Algebra I, Algebra II

1. **Commutative Algebra** Projective and injective modules, projective and injective resolutions, functors, chain complex, exact sequences, higher derived functors, functoriality
2. **Group cohomology:** Ext and Tor, group cohomology, group extensions, H^1, H^2
3. **Central simple algebras:** Simple modules, Schur's lemma, semisimple modules, central simple algebras, Wedderburn's decomposition theorem, tensor operation
4. **Brauer group:** Brauer group of a field, relation of Brauer group to Galois cohomomology of the field

Main Text Books:

1. N. Jacobson, Basic Algebra Vol. I and II, Second edition, W. H. Freeman and Company 1989
2. T. Y. Lam, A First Course in Non-Commutative Rings, Second edition, Graduate Texts in Mathematics, 131, Springer-Verlag, New York, 2001

Supplementary References:

1. N. S. Gopalkrishnan, Commutative Algebra, Oxonian Press Pvt. Ltd., New Delhi, 1984

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

5.7 Algebraic Topology (PM507)

Prerequisites: Basic knowledge of Topology and Group Theory

1. **The Fundamental group:** Homotopy of paths. Definition of the fundamental group, covering spaces, the fundamental group of a circle, retractions, Brouwer fixed point theorem for a disc
2. **Deformation Retracts and Homotopy Type**
3. **Fundamental groups of n-spheres and some surfaces**
4. **The Seifert-van Kampen Theorem:** Free products of groups, free groups, Seifert-van Kampen theorem, fundamental groups of wedge of circles and of tori
5. **Classification of Covering spaces:** Covering spaces, equivalence of covering spaces, universal covering space, covering transformations, existence of covering spaces
6. **Singular Homology:** Singular complex, singular homology groups, homotopy axiom, Hurewicz theorem relating the fundamental and homology groups
7. **Additional Topics:** Brief idea about simplicial homology, reduced homology groups, homology of spheres

Main Text Books:

1. J. R. Munkres, Topology, Second Edition, Pearson, 2000
2. J. J. Rotman, An Introduction to Algebraic Topology, Springer, 1988

Supplementary References:

1. A. Hatcher, Algebraic Topology, Cambridge University Press, 2002
2. G. E. Bredon, Topology and Geometry, Graduate Texts in Mathematics, 139, Springer, 1993
3. F. H. Croom, Basic concepts of Algebraic Topology, Undergraduate Texts in Mathematics, Springer. 1978
4. Anant R. Shastri, Basic Algebraic Topology, First edition, Chapman and Hall/CRC, 2013

BACK TO THE TABLE OF COURSES **BACK TO THE TABLE OF CONTENTS**

5.8 Banach and Operator Algebras (PM508)

Prerequisites: Real analysis, Basic Topology and Functional Analysis

1. **Banach algebras:** Banach algebras, ideals and quotients, invertible elements, spectrum and spectral radius, Spectral mapping theorem, Gelfand-Mazur theorem, commutative Banach algebras and their Gelfand representations, holomorphic functional calculus, quotients, Stone-Weierstrass theorem

2. **C*-algebras:** Banach *-algebras and C*-algebras, multiplier algebra, unitization, Gelfand-Naimark representation of commutative C*-algebras, functional calculus, spectral mapping theorem, positive elements of C*-algebras

3. **Operators on Hilbert spaces:** Spectrum and other properties of normal, self adjoint, projection and unitary operators, partial isometry, polar decomposition, finite-rank and compact operators, diagonalization, Hilbert-Schmidt operators, trace-class operators

4. **The Spectral Theorem:** Spectral measures, spectral theorem for normal operators

5. **Gelfand-Naimark Representation:** Ideals in C*-algebras, approximate units, quotients, positive linear functionals, Gelfand-Naimark representation of C*-algebras

6. **Additional Topics:** von Neumann algebras - Strong and weak operator topologies, commutants, von Neumann algebras, double commutant theorem, polar decomposition, projections, Calkin algebra, pre-dual of a von Neumann algebra, Kaplansky density Theorem, Abelian von Neumann algebras

Main Text Book:

1. G. J. Murphy, C^*-algebras and Operator Theory, Academic Press Inc., 1990

Supplementary References:

1. W. Arveson, A course on Spectral Theory, GTM, Springer, 2002

2. R. G. Douglas, Banach algebra techniques in Operator Theory, Second Edition, GTM, Springer, 1998

3. J. Dixmier, C^*-algebras, North-Holland Publishing Company, 1977

4. E. Kaniuth, A course on commutative Banach algebras, Graduate Texts in Mathematics, Springer, 2009

5. M. Takesaki, Theory of Operator Algebras I, Springer, 2002

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

5.9 Numerical Analysis (PM509)

Prerequisites: Basic analysis and algebra.

1. **Quick review of basic numerical computations and errors:** Floating point systems, Exact and approximate numbers, Rounding of numbers, Significant digits, accuracy, and various types of errors encountered in computations, order, and rate of convergence. Roots of algebraic and transcendental equations: Direct and Iterative methods with convergence criteria and error analysis.

2. **Solution of a system of equations: Direct methods:** Pivoting, Gauss elimination with pivoting, Tridiagonal systems, Thomas algorithm, Cholesky factorizations, SOR methods. Eigen-value problems: Power method, Givens method, Jacobi eigenvalue method, and Householder methods.

3. **Numerical solutions of IVPs and BVPs:** Single-step and multistep methods: Euler's method, Runge-Kutta methods, Adam-Bashforth method, Shooting, and finite difference methods.

4. **Solution of BVPs by Variational Methods:** Introduction, Variational principle, Ritz Method, Functional for a differential equation, Galerkin's Method, Collocation Method.

5. **Solution of BVPs by Finite Element Method:** Introduction, Ritz finite element method, Galerkin finite element method, Rayleigh-Ritz Method, and application on BVPs.

Suggested References:
Main Textbooks:

1. Richard L. Burden and J. Douglas Faires: Numerical Analysis, Ninth Edition, Brooks/Cole, Cengage Learning, 2011.

2. Kendall E. Atkinson: An introduction to numerical analysis, Second edition, John Wiley and Sons, 2008.

3. G. D. Smith: Numerical solution of partial differential equations: Finite Difference Methods, Third edition, Oxford University Press, 1985.

4. D. M. Causon, C. G. Mingham, and L. Own: Introductory Finite Volume Methods for Partial Differential Equations, Springer, 2009.

Supplementary References:

1. M. K. Jain, S. R. K. Iyengar, and R. K. Jain: Numerical Methods for Scientific and Engineering Computation. New Age International, 2012.

2. R. S. Gupta, Elements of Numerical Analysis, Macmillan India Ltd., 2009.

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

5.10 Computational Fluid Dynamics (PM510)

Prerequisites: Basic Calculus and Analysis.

1. **Unit I:** Concept of fluids, physical properties of fluids, continuum hypothesis, density, specific weight, specific volume, kinematics of fluids.

2. **Unit II:** Eulerian and Lagrangian method of description of flows, equivalence of Eulerian and Lagrangian methods, streamline, path line, streak lines, stream function, vortex lines, rotational and irrotational motion.

3. **Unit III:** General theory of stream function, complex-potential, stress, rate of strain, source, sink, and doublets, equation of conservation of mass (continuity equation), equation of conservation of momentum, Euler's equation of motion, Bernoulli's equation.

4. **Unit IV:** Mathematical description of physical phenomenon, finite control volume, Reynolds-transport theorem, Navier Stokes equation, equation of moments of momentum, equation of energy.

5. **Unit V:** Computational techniques to solve the flow models: Non-dimensionalization, Grid formulation and appropriate transformations, Lax-Wendroff Technique, MacCormack's Technique, Quasi-linearization, Spectral methods, Finite difference Method, Finite volume Method and bvp4c, bvp5c.

6. **Practicals:** Practicals will be performed on the MATLAB software.

   Spectral Method to solve the boundary value problem.

   Finite difference Method to solve the boundary value problem.

   Bvp4c and bvp5c methods to solve the boundary value problem.

Suggested References:
Main Text Books:

1. R. H. Pletcher, J. C. Tannehill and D. A. Anderson, Computational Fluid Mechanics and Heat Transfer, CRC Press, Taylor and Francis, 2013.

2. J. D. Anderson, Computational Fluid Dynamics, McGraw-Hill, 1995.

3. S. V. Patankar, Numerical Heat Transfer and Fluid Flow, CRC Press, Taylor and Francis, Indian Edition, 2017.

Supplementary References:

1. J. C. Strikwerda, Finite Difference Schemes and Partial Differential Equations, Second Edition, SIAM, 2004.

2. J. W. Thomas, Numerical Partial Differential Equations: Finite Difference Methods, Springer, 2013.

3. H. K. Versteeg, and W. Malalasekera, An Introduction to Computational Fluid Dynamics: The Finite Volume Method, Second Edition, Pearson, 2008.

4. S K Som, Gautam Biswas, S Chakraborty, Introduction to Fluid Mechanics and Fluid Machines, McGraw Hill Education, 3rd Edition, 2017.

5. C. A. J. Fletcher, Computational Techniques for Fluid Dynamics: Fundamental and General Techniques: 001, Springer Verlag, 2nd ed. 1998.

BACK TO THE COURSE TABLE **BACK TO THE TABLE OF CONTENTS**

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