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Master of Technology (M.Tech.) Programme in Modeling and Simulation

Board of Studies: Modeling and Simulation
Faculty of Technology, Savitribai Phule Pune University

Approved by Acadmic Council
Savitribai Phule Pune University

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About This Document

The *Master of Technology (M.Tech.) Programme in Modeling and Simulation*, designed by a core group of people associated with the Centre for Modeling and Simulation, Savitribai Phule Pune University (formerly University of Pune), was approved by the University in 2007, and came into existence in the academic year 2008-09. Based on the collective and individual experience gained since then, the present document outlines a university-approved revision of this programme.

Citing This Document

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Credits and Acknowledgements

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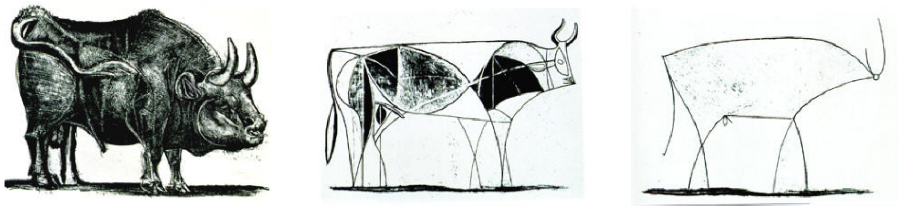
We Value Your Feedback

The utility of modeling and simulation as a methodology is extensive, and the community that uses it, academic or otherwise, is diverse. We would appreciate your feedback and suggestions on any aspect of this programme. Feedback can be sent to `office@cms.unipune.ac.in`.

About the Centre

The Centre for Modeling and Simulation, Savitribai Phule Pune University (formerly University of Pune), was established in August 2003 with a vision to promote modeling and simulation methodologies and, in keeping with worldwide trends of modern times, to encourage, facilitate, and support highly interdisciplinary approaches to basic and applied research that transcend traditional boundaries separating individual knowledge disciplines. For more information, visit `http://cms.unipune.ac.in/`.



All models are false, some are useful.
Quote attributed to George E.P. Box.

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Administrative Summary of the Revised M.Tech. Programme

Title of the Programme	Master of Technology (M.Tech.) Programme in Modeling and Simulation.
Degree Offered	Master of Technology (M.Tech.) in Modeling and Simulation.
Designed by	Centre for Modeling and Simulation, Savitribai Phule Pune University (formerly University of Pune).
Board of Studies	Modeling and Simulation
Faculty	Faculty of Technology, Savitribai Phule Pune University.
Mode of Operation	Full-time, autonomous programme run by the Centre for Modeling and Simulation, Savitribai Phule Pune University in the academic flexibility/autonomy mode.
Minimum Duration	2 years.
Number of Credits	100.
Credit Breakup	Semester 1: 25 core credits. Semester 2: 18 core and 7 choice-based credits. Semester 3: 15 core and 10 choice-based credits. Semester 4: 25 core credits.
Structure and Syllabus	This document, Sec. 2 onwards.
Medium of Instruction	English.
Number of Seats	Regular Admissions. 30. Supernumerary Admissions. Sponsored Candidates: up to 10% of the regular seats. Foreign Students, Kashmiri Students, Etc.: as per the prevailing Savitribai Phule Pune University policies.
Fees	Regular Admissions, Kashmiri Students, Foreign Students. As per the prevailing Savitribai Phule Pune University policies for self-supporting departments. Sponsored Candidates. 2 × regular fees for the Maharashtra open category.
Eligibility	B.E./B.Tech. any branch with mathematics at the Savitribai Phule Pune University M1+M2+M3 level
Admissions (First Year)	Regular Admissions Including Kashmiri Students. Performance in an entrance test to ascertain adequate mathematics background equivalent to the Savitribai Phule Pune University S.Y.B.Sc. mathematics syllabus, with a selection threshold/cutoff to be decided by the Centre for Modeling and Simulation and declared in advance. These admissions will be subject to the prevailing Savitribai Phule Pune University admission policy. Sponsored Candidates. First-come-first-served basis; separate entrance test if number of candidates greater than available seats. Foreign Students. Academic record, statement of purpose, and acceptable English language skills. Telephonic interview and/or letters of recommendation, if necessary, on a case basis.
Admissions (Second Year)	As per the prevailing Savitribai Phule Pune University norms. Currently, pass or better grade in at least 50% of the first-year credits.

1 The Revised M.Tech. Programme

1.1 What Has Not Changed

The *Master of Technology (M.Tech.) Programme in Modeling and Simulation*, publically available in the form of public document CMS-PD-20070223 (http://cms.unipune.ac.in/reports/pd-20070223/), was designed by a core group of people associated with the Centre for Modeling and Simulation, Savitribai Phule Pune University (formerly University of Pune) after extensive brain-storming and discussions, several preliminary revisions, and incorporating feedback from experts, both from academics as well as industry/corporate world. This programme was approved by the University in 2007, and came into existence in the academic year 2008-09. True to the vision with which the Centre was founded in 2003, namely, to

> *promote modeling and simulation methodologies and, in keeping with worldwide trends of modern times, to encourage, facilitate, and support highly interdisciplinary approaches to basic and applied research that transcend traditional boundaries separating individual knowledge disciplines,*

the programme's outlook and, consequently, its curriculum, have been multi-disciplinary to the core right from the beginning – The original programme document cited above amply corroborates this claim.

Therefore, what has *not* changed in this revision is

1. our philosophy and outlook on M&S;
2. our academic outlook including pedagogy, emphasis on concept over mathematical rigour, teacher's freedom in choosing the mode/model of course delivery, etc.;
3. the goals of the programme;
4. the broad content of the programme (i.e., applied mathematics, applied statistics, computing, and M&S); and
5. preference for open-source software over proprietary/commercial software.

In this connection, we refer the reader to sections 1 and 2, and appendix I of the original programme document cited above.

1.2 What Has Changed

The curriculum for the Master of Technology (M.Tech.) Programme in Modeling and Simulation has been revised in the light of

1. experience gathered while running the programme since 2008;
2. feedback from students, alumni, teachers, employers, and experts;
3. better understanding of the student audience for this programme;
4. changes in the outside world; and
5. greater emphasis on depth while reducing the breadth of the original programme slightly.

Major changes incorporated in this revision of the programme are as follows:

1. Greater emphasis on the M&S component of the programme so as to convey the spirit of M&S better, and revised structure and content for the M&S courses (Sec. 2). This point is further elaborated upon in Sec. 1.7.
2. Additions, deletions, and content changes to core and elective courses (Sec. 2 and 3).
3. Greater flexibility offered to the student in terms of choice-based credits with a view to make the programme more learner-centric (Sec. 1.4).
4. A focused professional development programme for the students (Sec. 1.6).
5. Revised operating guidelines, policies, and clarifications (the rest of this section).

1.3 Core Courses

Major changes to the core courses include

1. Technical communication and linux-related courses, which were part of the core curriculum in the original version, are now introduced as workshop-mode non-credit courses (Sec. 1.6).
2. The programming languages included in the core curriculum are `C`, `MATLAB/Scilab`, and `R`. `C++` has been dropped. `Java` is now offered as an choice-based elective course.
3. Based on feedback from alumni and experts, the course on high-performance computing is now offered as a choice-based course.
4. A full-fledged course on numerical linear algebra has similarly been downsized and subsumed into a numerical computing course.
5. The M&S courses, which form the heart of the curriculum, now have a better-defined structure and content.
6. Courses are now restructured to emphasize hands-on work and their "applied" aspect.
7. Courses on difference equations and discrete mathematics have been introduced in the curriculum.

Detailed syllabi for the core courses can be found in Sec. 2.

1.4 Choice-Based Courses (CBC)

Aligning the Master of Technology (M.Tech.) Programme in Modeling and Simulation with the UGC's recommendations for a choice-based credit system in spirit, the programme offers certain number of choice-based credits (Sec. 3). In contrast to an undergraduate student who is likely to consider and explore a wide range of educational and career possibilities, a postgraduate student is already far more specialized in her/his area of interest/expertise, and the choice (s)he would require is somewhat narrower compared to an undergraduate, and limited to technical areas of her/his interest or intended field of specialization. In the current curriculum, choice-based courses are offered in the second and third semesters once a student is adequately prepared for them in the first semester. Academic and procedural guidelines for choice-based/elective courses are as follows.

1. The in-house elective courses outlined in Sec. 3.
2. Any course proposed and approved by the Centre's faculty/departmental committee after thorough discussion and adequate revision, followed by approval from the Board of Studies. Proposal should provide motivation/justification for the course, a well-designed syllabus together with projected pedagogic and logistic requirements, and identify adequately qualified potential instructors (not necessarily from the Centre).
3. University-approved courses being offered at other University departments, centres, schools, affiliated entities outside the campus, and national institutes, provided the offering entity/instructor is willing to engage the interested students with adequate course work, a clear connection with M&S can be identified, and the Centre's faculty deems such a course as appropriate/suitable for the programme.
4. Ideally, it would be nice if the second elective taken by a student is a logical continuation of the first. However, this is not an absolute requirement, and a student may opt for electives on two separate topics, provided pre-requisites/dependencies as laid out by the syllabus and/or the instructor of the second course are satisfied.

5. A student needs to inform the Centre about her/his choice of elective courses for an upcoming semester at least a month in advance before the commencement of the semester. A student may be allowed to change their chosen elective/s within 3 weeks of the commencement of a semester, provided pre-requisites/dependencies of the second course are satisfied. This applies both to the students in the Master of Technology (M.Tech.) Programme in Modeling and Simulation, as well as Savitribai Phule Pune University students wishing to take credit courses at the Centre.
6. A student in the Master of Technology (M.Tech.) Programme in Modeling and Simulation may take 17 credits worth of choice-based courses during semesters 2 and 3.

1.5 Internship

Continuing with the original vision of the programme, and based on the positive feedback from advisors/mentors from industry and academics alike, we have retained a full-semester full-time 25-credit internship component in the curriculum. In our experience, this ensures substantial hands-on experience and domain-specific training, allows for out-of-town internships, thus maximizing a student's prospects for employment. Detailed information including operational guidelines, pre-requisites, etc., for this component can be found in Sec. 2.25.

The internship component of the Master of Technology (M.Tech.) Programme in Modeling and Simulation may also be considered choice-based, because the choice of place, advisor, and topic of internship lies entirely with the student, provided the internship is aligned with the overall goals of the programme.

1.6 Professional Development Programme (PDP)

Recognizing certain shortcomings in the average student's background and grooming, we have designed a *professional development programme* (PDP) for the students in the Centre's academic programmes. This programme will be run every semester in a workshop mode with the help of in-house and/or outside experts. Parts of the this programme may be offered for a fee as certificate courses open to the public. For students in the Master of Technology (M.Tech.) Programme in Modeling and Simulation, these workshops will be treated as additional 1-credit courses requiring mandatory attendance and participation, but without any assessment, evaluation, or grading. Focus statements, rather than "syllabi", can be found in Sec. 4.

The *Professional Development Programme* (PDP) consists of two course streams (namely, `linux` operating system and technical communication) that were part of the original curriculum, plus a *life skills* component. The *life skills* component of the PDP is motivated by the fact that many post-graduate students appear to lack independence, motivation, resourcefulness, and self-study skills; problem-solving skills; ability to think and organize knowledge; ability to make connections across courses; time and work management skills; and sometimes even the basic skills such as attention, listening, reading, and self-study that are taken for granted (see, e.g., Sec. I.1 of the original programme document `http://cms.unipune.ernet.in/reports/pd-20070223/`). This often results into a mindless pursuit of degrees without enhancing real capabilities, skills, or knowledge. This stream of the PDP is an attempt to make a student aware of possibilities and techniques that can help her or him be better-prepared for the world. The *life skills* component will be conducted with the help of qualified experts such as psychologists.

1.7 The M&S Course Stream

A criticism on the earlier curriculum for the programme was that it was dominated by mathematics courses. The current revision has achieved to strike a better balance between the various

groups of courses in the curriculum. Specifically, excluding choice-based and internship credits, the credit breakup for the four principal groups is as follows:

Course Group	Courses	Credits (%)
Mathematical	C101–C107, C201, C203	19 (33%)
Computing	C108–C110, C202, C205, C301	10 (17%)
Statistical/Stochastic	C204, C206, C302, C303	12 (21%)
M&S	C111, C207, C304, C305	17 (29%)

Percentages reported with respect to core credits (58); this excludes internship (25) and choice-based credits (17).

We would like to point out the following in this regard.

1. The M&S course sequence C111 – C207 – C304 is based on the philosophical viewpoint of first exposing the student to M&S ideas through hands-on work, and then presenting knowledge organization and systematization in the end.
2. The M&S course sequence C111 – C207 – C305 can be thought of as reducing the student group size from entire class to individual, gradually driving a student towards independence, eventually culminating into the Internship C401.

1.8 Interpreting Syllabi

The syllabi in Sec. 2, 3, and 4 are to be considered indicative of the overall focus and scope of the respective courses. Actual coverage of topics, their relative emphasis, and choice of modeling contexts may vary at the discretion of a competent instructor without compromising upon the essential content and the goals for the course. Topics marked Optional may be covered or not covered at the discretion of the instructor, the consideration here being the batch-to-batch variation in the students' backgrounds, capabilities, and interests. The overall outlook on pedagogy (e.g., emphasizing concept and clarity over mathematical rigour; see Sec. I.2 of the original programme document (http://cms.unipune.ernet.in/reports/pd-20070223/) continues to underline the programme. Individual courses have been assigned two types of course attribution: (a) Exactly one out of the set {Core, CBC, PDP}; and (b) one or more out of the set of {C (classroom), T (tutorial), L (laboratory), S (seminar), W (workshop)}. The (b)-attributions are suggestive of the pedagogic distribution of the course and of how the course may be conducted.

1.9 Grading, Evaluation, Assessment

We follow prevailing University policies and practices in this regard. Currently, continuous and final assessments have 50% weight each. It is also customary in the University to grade students using marks and then convert the resulting percentages to grades as per the University-prescribed norms. Beyond this, the teacher is the best judge of the mode/model of assessment for her/his course. On academic grounds, we refrain from making rigid and un-academic connections between nominal marks and duration of examination. Following the spirit of the choice-based credit system, and in the best interest of the student, we also believe that final assessment/examination for a credit course should be at the end of the course, and not necessarily at the end of the semester. Grades will be reported on the University-recommended 10-point grade scale[1], or as per the prevailing rules and norms of the University.

[1] http://www.unipune.ac.in/university_files/pdf/CBCS-Handbook-28-7-15.pdf

1.10 The Student: Assumptions and Time Budgeting

In formulating this intensive full-time programme, we have assumed that the student has

1. adequate level of motivation and interest in the programme, adequate time at hand, and the ability to work hard; and
2. adequate background in mathematics, and capability of absorbing and assimilating the programme content.

Specifically, we have assumed that, *on the average*, the student will be able to put in 1–1.5 hours of self-study for every hour of intensive academic engagement (i.e., classroom sessions). Given these assumptions, and reasonable assumptions about personal and commute time,

1. intensive academic engagement (i.e., classroom sessions), *on the average*, should not be more than 5 clock hours on a typical working day;
2. any additional engagement, if necessary, should allow enough time for self-study, completion of assignments, etc.; and
3. Centre's library, computational laboratories, and internet/network resources should be available to the student after office hours as well, and should be adequate in capacity to accommodate all admitted students simultaneously.

1.11 Placement Activities

Potential students often ask whether the Centre organizes campus placement activities. Ideally, campus placement activities should be run in an organized manner at the University level, where numbers and diversity are the key attractions for potential employers to engage with students. If this is not feasible, then we believe that campus placement is an area that is primarily *of the students, by the students, for the students*, and the Centre can at best be in a passive supportive role. The Centre thus encourages and supports students in organizing such activities themselves or in collaboration with students from other University departments, schools, or centres.

2 Core Credits

2.1 Structure of the Core Curriculum

Semester 1

Core credits: 25, choice-based/elective credits: 0

Code (Section)	Course Name	Credits
C101 (2.2)	Real Analysis and Calculus	2
C102 (2.3)	Vector Analysis	2
C103 (2.4)	Linear Algebra	2
C104 (2.5)	Ordinary Differential Equations	2
C105 (2.6)	Partial Differential Equations	3
C106 (2.7)	Probability Theory	3
C107 (2.8)	Computing with `R`	1
C108 (2.9)	Computing with `MATLAB/Scilab`	1
C109 (2.10)	Computing with `C`	2
C110 (2.11)	Algorithms	2
C111 (2.12)	M&S Hands-On 1	5

Semester 2

Core credits: 18, choice-based/elective credits: 7

Code (Section)	Course Name	Credits
C201 (2.13)	Complex Analysis	2
C202 (2.14)	Transforms	2
C203 (2.15)	Difference Equations	2
C204 (2.16)	Numerical Computing 1	2
C205 (2.17)	Optimization 1	2
C206 (2.18)	Statistical Inference	3
C207 (2.19)	M&S Hands-On 2	5

Semester 3

Core credits: 15, choice-based/elective credits: 10

Code (Section)	Course Name	Credits
C301 (2.20)	Numerical Computing 2	2
C302 (2.21)	Optimization 2	3
C303 (2.22)	Stochastic Simulation	3
C304 (2.23)	M&S Overview	4
C305 (2.24)	M&S Apprenticeship	3

Semester 4

Core credits: 25, choice-based/elective credits: 0

Code (Section)	Course Name	Credits
C401 (2.25)	Internship	25

2.2 C101 Real Analysis and Calculus

Credits. 2

Prerequisites. None

Dependent Courses. C105 (2.6), C201 (2.13), C202 (2.14), C203 (2.15), E001-1 (3.2)

Attributions. Core; C, T

Rationale, Outlook, Purpose, Objectives, and Goals. Ability to apply standard calculus techniques with good comfort levels regarding their basic understanding. The student should also be able to handle real numbers and their analysis as much as outlined in the syllabus. If the student so desires, he/she should be able to build upon this preparation independently to delve into elementary understanding (including proofs and heuristics) as and when needed in later courses.

Syllabus.

1. Basics of set theory, relations and functions.
2. Introduction to metric spaces, open and closed sets, countable sets.
3. Real numbers, real sequences, infinite series, convergence and tests of convergence.
4. Real functions of single and several real variables, plotting graphs of such functions, limits, continuity and uniform continuity.
5. (For real functions of one real variable:) Derivative, Rolle's and Lagrange mean value theorems, Taylor's theorem, order notation and concept of infinitesimal, extreme values and indeterminate forms.
6. (For real functions of several real variables:) Differentiability, Young and Schwarz theorems, partial derivatives, Taylor's theorem and extreme values, homogeneous functions and Euler's theorem, implicit functions, Jacobians.
7. Revision of integration of functions of one variable, definition, standard results and methods of integration, interpretation as area under graph, infinitesimals and Riemann sums.
8. Double integration with procedure and interpretation, Fubini's theorem, change of variables.
9. Triple integration with procedure.

Suggested Texts/References.

1. S. C. Malik and Savita Arora, *Mathematical Analysis*. New Age Publishers, 2009.
2. Erwin Kreyszig, *Advanced Engineering Mathematics*. Wiley India, 2014.

Notes on Pedagogy. Depending upon the capacity of the batch of students, previous orientation and training, the teacher can adjust the depth of delivery so as to best meet the objective. The content can also be tuned accordingly. The content could even be ordered and modified according to the presentation in the prescribed text book/s.

Contributor/s. Sukratu Barve (http://cms.unipune.ac.in/~sukratu)

2.3 C102 Vector Analysis

Credits. 2

Prerequisites. None

Dependent Courses. C201 (2.13), C202 (2.14), C203 (2.15), E001-1 (3.2)

Attributions. Core; C, T

Rationale, Outlook, Purpose, Objectives, and Goals. This foundational course is intended to bring the student at an acceptable level of understanding of vector analysis so that (s)he is able to assimilate related material in advanced courses later on in the programme.

Syllabus.

1. Scalar and vector fields, surfaces and curves in space, examples using analytical geometry, parametric equations for curves and surfaces, intrinsic dimension of subsets of background space using analytical geometry.
2. Continuity and differentiability of vector and scalar fields. Partial derivatives of vectors and scalar fields, the vector operator ∇.
3. Gradient of a scalar field, level surfaces, directional derivative and interpretation of gradient, tangent plane and normal to level surfaces.
4. Divergence and curl expressions. Important vector and scalar calculus identities.
5. Flux of a vector field through a surface portion with an example calculation.
6. Gauss Divergence theorem and outline of proof. Interpretation of divergence in terms of flux.
7. Vector line differential and integral with example calculations.
8. Deriving Green's theorem in a plane. Definition of vector line integral (for 2D vectors on a plane) and relation to Green's theorem.
9. Stokes' theorem and outline of proof (e.g., using Green's theorem). Interpretation of curl in terms of vector line integrals.
10. Conservative vector fields, line integrals and gradients: basic results with proofs, irrotational and solenoidal vector fields.

Suggested Texts/References.

1. Erwin Kreyszig, *Advanced Engineering Mathematics*. Wiley India, 2014.
2. A. R. Vasishtha and Kiran Vasishtha, *Vector Calculus*. Krishna Prakashan Media, 2007.
3. Anil Kumar Sharma, *A Textbook of Vector Calculus*. Discovery Publishing House, 2006.
4. Shanti Narayan and P. K. Mitta, *A Textbook of Vector Calculus*. S. Chand, 1987.

Notes on Pedagogy.

Contributor/s. Sukratu Barve (`http://cms.unipune.ac.in/~sukratu`)

2.4 C103 Linear Algebra

Credits. 2

Prerequisites. None

Dependent Courses. C201 (2.13), C202 (2.14), C203 (2.15), E001-1 (3.2)

Attributions. Core; C, T

Rationale, Outlook, Purpose, Objectives, and Goals. This foundational course is intended to bring the student at an acceptable level of understanding of linear algebra so that (s)he is able to assimilate related material in advanced courses later on in the programme.

Syllabus.

1. Introduction to Matrices. Definition and examples, types of matrices, operations on and of matrices (row, column, sum, product, transpose, inverse, Hermitian adjoint) submatrices, determinants, rank, basic theorems on row and column operations on products, theorem on rank of product, elementary matrices, minors, Cofactors, and Cofactor adjoint of a matrix, relation to inverse, standard properties of matrices,symmetry and similarity transformations of matrices.
2. Systems of Linear Equations. Examples, solution methods (Gauss elimination), matrix representation and row echelon form of matrices, basic and free variables, consistency, number of independent equations, Gauss-Jordan Elimination, Cramer's rule and derivation, LU and LDU decomposition.
3. Vector Spaces. Outline of abstract algebra, groups, rings and fields. Definition of vector space over a field and examples of 3D vectors,functions,matrices and their appearance in context of statistics and engineering. Basic results following immediately from axioms. Vector subspaces, linear independence, span, bases, uniqueness of coefficients, dependence theorem, dimension and its uniqueness, direct sums, Transformation of bases.
4. Linear Operators. Definition and properties following immediately from definition. Null space and range. Bases and representation of linear operators as matrices, transformation of operator matrices according to basis transformations, examples.
5. Inner Product Spaces. Definition and basic properties, examples in 3d vectors and spaces of functions, Bessel inequality, Cauchy-Schwarz inequality, Norm from inner product and independent definition of norm. Parallelogram and polarization identities. Angle between vectors and orthogonality (with examples from function spaces). Orthogonal complement of a subset, Orthonormal vectors, their linear independence, Gram-Schmidt Orthogonalization, projection operators and orthogonal projection operators, QR decomposition.
6. Eigenvalues, Eigenvectors and Diagonalization. Definition of eigenvectors and eigenvalues of linear operators. Basic results. Calculation using matrix representations. Diagonalization using a particular similarity transformation, application in linear equations and linear ODEs, normal matrices and diagonalizability, spectral theorem for normal matrices.
7. Quadratic forms. Definition, matrix of quadratic form and its symmetrization, definiteness, symmetry transformations and diagonal form, signature, Sylvester's law of inertia, criteria for definiteness, semidefiniteness and indefiniteness. Introduction to higher-degree forms.

Suggested Texts/References.

1. A.K. Lal, *Notes on Linear Algebra*. NPTEL, 2013. http://home.iitk.ac.in/~arlal/book/nptel/pdf/book_linear.pdf
2. Kanti Bhushan Datta, *Matrix and Linear Algebra*. Prentice Hall India, 2008.
3. S. Kumaresan, *Linear Algebra: A Geometric Approach*. Prentice Hall India, 2000.
4. S.K. Mapa, *Higher Algebra: Abstract and Linear*. Levant Books, 2011.
5. Seymour Lipschutz and Marc Lipson, *Linear Algebra (Schaum Series)*. McGraw-Hill India, 2005.
6. Otto Bretscher, *Linear Algebra with Applications*. Pearson, 2008.
7. Paul Halmos and John L. Kelley, *Finite Dimensional Vector Spaces*. Literary Licensing, LLC, 2013.
8. Anil Kumar Sharma, *Linear Algebra*. Discovery Publishing House, 2007.
9. Georgi Shilov, *Introduction to the Theory of Linear Spaces*. Martino Fine Books, 2013.

Notes on Pedagogy.

Contributor/s. Sukratu Barve (http://cms.unipune.ac.in/~sukratu)

2.5 C104 Ordinary Differential Equations

Credits. 2

Prerequisites. C105 (2.6)

Dependent Courses. C107 (2.8)

Attributions. Core; C, T

Rationale, Outlook, Purpose, Objectives, and Goals. This and two sister courses C105 (2.6) and C107 (2.8) aim at developing commonly-used modeling formalisms for describing change.

Syllabus.

1. Definition of an ordinary differential equation, order and degree along with examples, Definition of solution. General particular and singular solutions, homogeneous functions.
2. First order ODEs having homogeneous functions. Shift of origin change of variables for converting to homogeneous form. Exact first order ODEs. Standard examples of exact ODEs. Integrating factors. Standard examples of integrating factors in various categories of first order ODEs. Linear first order ODEs and integrating factor, Bernoulli's ODE First order ODEs with higher degree and methods of solution (solvable for x, y or dy/dx) Clairaut's form of first order ODE.
3. Second order ODEs (homogeneous and non-homogeneous).
4. ODEs with constant coefficients, (optional examples of analysis of spring-mass-dashpot system) differential operator and its polynomial, complementary and particular integrals, general procedure of obtaining solution.
5. ODEs with variable coefficients, method of variation of parameters (only in case of second order ODEs)
6. Revision of sequences, series and convergence. Series of functions, Power series, ratio test, radius of convergence, series solutions of ODEs, method exemplified in particular cases (second order ODEs) Bessel, Hermite and Legendre ODEs and their series solutions. Brief outline of special functions and their properties.
7. Side conditions of ODEs and their illustration in all the above techniques.
8. Conversion of higher order ODEs into first order ODEs with several dependent variables. Linear ODEs with several dependent variables, matrix formulation, interpretation of characteristic vectors and characteristic values, stability. Applications of this in perturbation of ODEs. Discussion of examples of 6 DOF analysis, control systems stability criteria, predator-prey and chemical reaction ODEs.
9. Numerical methods. Truncation, concept and implementation, forward backward and central difference schemes. Reference to difference equations. Concepts of consistency and stability. Iterative algorithms for solution of difference equations eg. Euler, Heun and Runge Kutta methods. Implicit methods and matrix inversion techniques of solution. Convergence of solutions. Lax theorem (without proof) Computer exercises (3 examples for explicit and 3 for implicit schemes).
10. (OPTIONAL) Existence and uniqueness of solutions of first order ODEs, normed vactor space techniques, uniform continuity, Lifshitz functions and outline of Picard's theorem. Linear ordinary differential operators and resolvents. Examples of resolvents in common

linear ODEs. Relation of side conditions to resolvents. Qualitative analysis of ODEs: Limit sets, fixed points, limit cycles, basins of attractors, Poincare Bendixson theorem (without proof) Lienard's theorem (without proof).

Suggested Texts/References.

1. S. Balachandra Rao and H. R. Anuradha, *Differential Equations with Applications and Programs*. Universities Press, 1996.
2. E. Rukmangadachari, *Differential Equations*. Dorling Kindersley India, 2012.
3. A. Chakrabarti, *Elements of Ordinary Differential Equations and Special Functions*. New Age International, 1990.
4. E. A. Coddington and N. Levinson, *Theory of ordinary Differential Equations*. Tata-McGraw Hill, 1972.
5. G. F. Simmons, *Differential Equations with Applications and Historical Notes*. Tata-McGraw Hill, 1991.
6. G. F. Simmons and S. G. Krantz, *Differential Equations: Theory, Techniques and Practice*. Tata-McGraw Hill, 2007.

Notes on Pedagogy.

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2.6 C105 Partial Differential Equations

Credits. 3

Prerequisites. C106 (2.7)

Dependent Courses. None

Attributions. Core; C, T

Rationale, Outlook, Purpose, Objectives, and Goals. This and two sister courses C105 (2.6) and C106 (2.7) aim at developing commonly-used modeling formalisms for describing change.

Syllabus.

1. Definition of partial differential equation. Order, dependent and independent variables, themes of classification and standard categories, first and second order PDEs; Laplace, heat and wave equations as basic examples of linear second order PDEs. Examples of higher order and non linear PDEs.
2. Cauchy Problems for First Order Hyperbolic Equations. Method of characteristics, Monge cone.
3. Classification of Partial Differential Equations. Normal forms and characteristics for second order PDEs. Principal symbol and quasilinear PDEs, classification of quasilinear PDEs, types of side conditions and principal symbols. General types of side conditions occurring in applications of hyperbolic, parabolic and elliptic PDEs.
4. Initial and Boundary Value Problems. Lagrange-Green's identity and uniqueness by energy methods.
5. (Optional) Stability theory. Energy conservation and dispersion.
6. Laplace equation. Mean value property, weak and strong maximum principle, Green's function, Poisson's formula, Dirichlet's principle, existence of solution using Perron's method (without proof).
7. Heat equation. Initial value problem, fundamental solution, weak and strong maximum principle and uniqueness results (outline of proofs and emphasis on interpretations)
8. Wave equation. Uniqueness, D'Alembert's method, method of spherical means, Duhamel's principle: outline of proofs with emphasis on interpretation.
9. Methods of separation of variables for heat, Laplace and wave equations. Various other methods of solution of PDEs and brief descriptions.
10. Finite difference method as numerical methods for PDEs. Finite Difference Operators, Finite Difference methods, FDM for 1D heat and wave equations, implicit and explicit methods of solution,method of lines,Jacobi, Gauss Seidel and Relaxation methods (for 2D Laplace and Poisson equations) von Neumann stability for difference equations and applications to 2D heat and wave equations. Stability and convergence of matrix difference methods.

Suggested Texts/References.

1. Erich Zauderer, *Partial Differential Equations of Applied Mathematics*. Wiley, 2006.
2. K. Sankara Rao, *Introduction to Partial Differential Equations*. PHI Learning, 2010.

3. Phoolan Prasad and Renuka Ravindran, *Partial Differential Equations*. New Age Publishers, 2012.
4. Lokenath Debnath, *Nonlinear Partial Differential Equations for Scientists and Engineers*. Birkhäuser, 2011.
5. Lawrence C. Evans, *Partial Differential Equations*. American Mathematical Society, 2010.

Notes on Pedagogy.

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2.7 C106 Probability Theory

Credits. 3

Prerequisites. None

Dependent Courses. C206 (2.18), C302 (2.21), C303 (2.22)

Attributions. Core; C, T

Rationale, Outlook, Purpose, Objectives, and Goals. Probability is the mathematical language for quantifying uncertainty or ignorance, and is the foundation of statistical inference and all probability-based modeling. Goals: Good understanding of probability theory as the basis for understanding statistical inference; familiarity with basic theory and pertinent mathematical results; emphasis on illustrating formal concepts using simulation; and some perspective on modeling using probability by way of real-life contexts and examples.

Syllabus.

1. Probability. Sample spaces and events. Probability on finite sample spaces. Independent events. Conditional probability. Bayes' theorem.
2. Random Variables. Distribution functions and probability functions. Important discrete and continuous random variables. Bivariate and multivariate distributions. Independent random variables. Conditional distributions. Important multivariate distributions. Transformations on one or more random variables.
3. Expectation. Properties. Variance and covariance. Expectation and variance for important random variables. Conditional expectation. Moment generating functions.
4. Inequalities for Probabilities and Expectations. Markov, Chebychev, Hoeffding, Mill, etc. Inequalities for expectation: Cauchy-Schwartz, Jensen, etc.
5. Convergence and Limit Theorems. Notion of convergence for random variables. Types of convergence. Law of large numbers, central limit theorem, the delta method.
6. Stochastic Processes (Optional). Basic introduction to simple branching processes, random walks, Markov chains, etc.

Suggested Texts/References.

1. Christopher R. Genovese, *Working With Random Systems: Mechanics, Meaning, and Modeling*. Unpublished, 2000. http://www.stat.cmu.edu/~genovese/books/WWRS.ps
2. Charles M. Grinstead and J. Laurie Snell, *Introduction to Probability*. American Mathematical Society, 1997. https://math.dartmouth.edu/~prob/prob/prob.pdf
3. Morris deGroot and Mark Schervish, *Probability and Statistics*. Addison-Wesley, 2002.
4. Larry Wasserman, *All of Statistics*. Springer-Verlag, 2004 (Part 1 of the book).
5. David Stirzacker, *Elementary Probability*. Cambridge University Press, 1994.

Notes on Pedagogy. This course can go hand-in-hand with the *Computing with* `R` course C107 (2.8). For example, `R` can be used liberally to illustrate (by the instructor) and explore (by the student) probability-related concepts and important results such as the central limit theorem.

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2.8 C107 Computing with R

Credits. 1

Prerequisites. None

Dependent Courses. C206 (2.18), C303 (2.22)

Attributions. Core; L

Rationale, Outlook, Purpose, Objectives, and Goals. The R (http://cran.r-project.org/) statistical computing environment, built around the S programming language, is rich in computational statistics primitives. It is open-source and supported by an ever-growing community of users and contributors. It allows a variety of programming styles from quick-and-dirty explorations to elaborate imperative, procedural, object-oriented, and functional coding. It is ideally suited for statistical modeling and data analysis, graphics and visualization, as well as a platform for teaching/learning probability and statistics through hands-on exploration. As such, R is a must for any broad-based M&S curriculum with a statistical modeling/data analysis component. Goals: proficiency in computational problem-solving using R; specifically, decent algorithmic, coding, and scripting skills.

Syllabus.

1. Overview of R and S. History of R. Why use R? When not to use R? GUIs for R. Invoking and exiting the R interpreter environment. Getting help and finding information. `demo()`. The six atomic types. Assignment operators. Standard arithmetic and logical operators. Comments. Conditionals and loops. Parenthesis and braces. Expressions. Every expression has a value. Common composite data types: `vector`, `list`, `matrix`, and `data.frame`. The elementwise operations rule for `vector` and related container types. `functions`. Writing and executing R scripts: `source()` and `Rscript`.
2. Case studies illustrating R capabilities, in-built functions, and common packages. Overview of R graphics. Probability distributions and random number generators. Creating numerical and graphical data summaries, and exploratory data analysis. Complex numbers, numerical methods, etc. Character strings. Set operations. Interface to the operating system shell. Data input and output.
3. Installing R and R packages locally into a linux user account. Installing R from source: `configure` – `make` – `make install` sequence. Installing packages: `install.packages()` and the `R CMD INSTALL` mechanism.
4. Migrating from C to R. Automatic type identification in an assignment vs. explicit declaration of data type. `;` and `\n` as expression terminators. Explicit loops vs. vectorization.
5. Getting performance from R codes. Coding style guidelines. Explicit loops vs. vectorization. The `compiler` package. Debugging and profiling tools. Interfacing with `C, C++, fortran`.
6. Hands-on explorations using R. Any reasonable set of hands-on problems designed to enhance computational problem-solving and algorithmic abilities. Such problems may be related to M&S in general, or specifically to topics from other courses (e.g., probability theory, statistical inference) in the programme or the instructor's field of expertise.

Suggested Texts/References.

1. W. N. Venables, D. M. Smith, and the R Development Core Team, *An Introduction to R*. The R Project, latest available edition. http://cran.r-project.org/doc/manuals/R-intro.html
2. John Verzani, *Using R for Introductory Statistics*. Chapman & Hall/CRC, 2005.
3. Daniel Navarro, *Learning Statistics with R: A Tutorial for Psychology Students and Other Beginners*. Self-published, 2013. http://learningstatisticswithr.com/
4. Paul Murrell, *R Graphics*. Chapman & Hall/CRC, 2011.
5. Patrick Burns, *The R Inferno*. http://www.lulu.com/, 2012. Available at http://www.burns-stat.com/documents/books/the-r-inferno/.
6. W. N. Venebles and B. D. Ripley, *Modern Applied Statistics with S-Plus*. Springer, 2002.
7. R. G. Dromey, *How to Solve It By Computer*. Prentice-Hall, 1982.

Notes on Pedagogy. This syllabus is based on an outline for a longer course that was refined over several course deliveries by the contributor (see below). Depending on the background and capabilities of the students, this outline may need to be somewhat diluted or intensified – without compromising upon the essentials and goals for the course. Apart from familiarizing a student with R, a major emphasis of this course is on tinkering and exploration, on computational problem-solving, and on translating a problem into a computational framework leading to either a solution or a better understanding of the problem, and on how R can be used as a M&S tool, and for exploring/visualizing probability and statistics concepts. Assignments often consist of problems that are exploratory in nature (e.g., illustrating formal results that may be difficult to grasp, such as the central limit theorem; see C106 (2.7)), or require a student to understand an algorithm from its plain-English or pseudocode description (e.g., generating the next permutation given a permutation of n objects). Examinations may consist of problems not necessarily discussed in the class: Here, adequate information about the method of solution or algorithm is provided.

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2.9 C108 Computing with MATLAB/Scilab

Credits. 1

Prerequisites. None

Dependent Courses. None

Attributions. Core; L

Rationale, Outlook, Purpose, Objectives, and Goals. MATLAB and its open-source parallel Scilab are popular, powerful, and flexible platforms for numerical and symbolic computation, visualization and graphics, etc., and are rich in computational primitives for diverse fields from digital signal processing to statistics. This course aims at developing an intermediate skill level in writing scripts, performing calculations, using the command line, importing data from files, plotting data, and integrating with other programming languages such as C.

Syllabus.

1. Introduction. Environment. Workspaces. General syntax.
2. Numerics. Creating matrices. Matrix operations. Sub-matrices. Statistical operations. Polynomials, differential equations.
3. Plots. Plotting graphs for 2D, 3D functions. Various types of plots.
4. Programming. Functions, Scilab/MATLAB programming language, Script files and function files.
5. I/O. Reading, writing data in various formats.
6. Interfacing with programming languages such as C.

Suggested Texts/References.

1. Amos Gilat, *MATLAB: An Introduction with Applications*. Wiley, 2008.
2. Mathews and Fink, *Numerical Methods Using MATLAB*. Pearson, 2004.
3. J. C. Polking and D. Arnold, *Ordinary Differential Equations using MATLAB*. Pearson, 2003.
4. An extensive comparison of MATLAB and Scilab: http://www.professores.uff.br/controledeprocessos-eq/images/stories/Comparative-Study-of-Matlab-and-Scilab.pdf

Notes on Pedagogy. Case studies and problems used for introducing MATLAB/Scilab should ideally be derived from other courses (e.g., differential equations C106 (2.7), C107 (2.8)) running concurrently.

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2.10 C109 Computing with C

Credits. 2

Prerequisites. None

Dependent Courses. C201 (2.13), C202 (2.14), E005 (3.10), E006 (3.11)

Attributions. Core; L

Rationale, Outlook, Purpose, Objectives, and Goals. Upon successful completion of this course, the student is expected to be able to

1. Understand basics of procedural/functional programming, syntax, semantics of C.
2. Design an algorithm to solve problems of various kinds in modeling and simulation and implement using C programming language.
3. Debug the code to spot logical errors, exceptions etc.
4. Write reasonably complex C code for solving various problems in modeling and simulation.

Syllabus.

- ANSI C. Syntax, data types, concept of void, variables, operators, expressions and statements, character input and output, console input and output, inclusion of standard header files, pre-processor directives.
- Control flows. If-else, for, while, do-while, switch-case, break and continue, code blocks and nesting of blocks.
- Functions. Basics of functions, return statement, recursion, function blocks, static variables
- Memory management. Dynamic versus static memory allocation, freeing memory, arrays, memory layout of multidimensional arrays.
- Pointers. Concept of pointers, pointer arithmetic, pointers versus arrays, array of pointers.
- Program compilation and debugging techniques. Introduction to tools like `gdb` together with `ddd`, `GNU make` and profiler `gprof`. Code organization across files. Version/revision control using `svn` or `git`.
- Structures and Unions. Structures and unions, bit fields, typedef, self referential structures, their use in link-list, queue, stack *etc.*
- Input and output in C. Files, file operations.

Suggested Texts/References.

- Kernighan and Ritchie, *The C Programming Language*. PHI, 1990.
- R. L. Kruse, B. P. Leung, C. L. Tondo, *Data Structures And Program Design In C*. Pearson Education, 2007.

Notes on Pedagogy. Although finite-precision arithmetic is covered at length in the course C201 (2.13), the student may be exposed here to the bare-basics of finite-precision representations and arithmetic if time permits, and at the discretion of the instructor.

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2.11 C110 Algorithms

Credits. 2

Prerequisites. None

Dependent Courses. C303 (2.22), E005 (3.10), E006 (3.11), E008 (3.13)

Attributions. Core; C, L

Rationale, Outlook, Purpose, Objectives, and Goals. This is intended to be an introduction to algorithms for a non-computer-science graduate student. In principle, any programming language (`C`, `Python`, `Haskel`, `LISP`, etc.) can be used for illustrating algorithms, at the discretion of the instructor. However, `C` is highly recommended so as to give student a closer feel of computer system organization. Please see the sister course C109 (2.10). This course is intended for

- familiarizing the student with the computer system organization and its use for problem solving;
- making student understand the need for formal algorithm development; and
- introducing basic types of algorithms, design techniques, data structures used for problem solving.

Syllabus.

1. Introduction to Algorithms. What is an algorithm, why do we need it? Introduction to fundamental algorithms like counting, sorting; algorithms for problem solving using digital computers, flow chart and pseudocode techniques. [5-6 hrs.]
2. Algorithms. Fundamental algorithms and techniques, data structures required (queue, FIFO, FILO, LIFO, LILO terminologies, stacks, link-lists, trees and graphs), logic, set theory, functions, basics of number theory and combinatorics (sequences-series, Sigma and PI notations for termwise summation, multiplication, probability, permutations, combinations), mathematical reasoning–including induction. [10-12 hrs.]
3. Recursion. Need, advantages, disadvantages. Recurrence analysis. Introduction to recurrence equations and their solution techniques (substitution method, tree recursion method, master method). Proof of the master method for solving recurrences. Demonstration of the applicability of master theorem to a few algorithms and their analysis using recurrence equations. Example algorithms: binary search, powering a number, Strassen'S matrix multiplication, etc. [10-12 hrs.]
4. Types of Algorithms and Their Analysis. Theta and big-theta notation, θ and Θ notations; comparison of algorithms, notions of space and time efficiency; as an illustrative example, comparison of quick-sort algorithm with other sorting algorithms can be demonstrated. [5 hrs.]

Suggested Texts/References.

- V. Rajaraman, T. Radhakrishnan, *An Introduction to Digital Computer Design.* PHI, 2007.
- T. H. Cormen, C. E. Leiserson, R. L. Rivest, C. Stein, *Introduction to Algorithms.* PHI Learning, 2009.

- D. E. Knuth, *The Art of Computer Programming, Vol. 1.* Addison Wesley, 2011.
- A. V. Aho, J. E. Hopcroft, J. D. Ullman, *Design and Analysis of Algorithms.* Pearson Education, 2011.
- E. Horowitz, S. Sahni, *Fundamentals of Computer Algorithms.* Universities Press, 2008.

Notes on Pedagogy.

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2.12 C111 M&S Hands-On 1

Credits. 5

Prerequisites. None

Dependent Courses. C207 (2.19)

Attributions. Core; C, L, S

Rationale, Outlook, Purpose, Objectives, and Goals. It is a challenge to communicate the depth of the sense in which modeling and simulation are to be understood. This course stems from the belief that a hands on experience can build the intuition more strongly than any other pedagogic technique. It proposes a reasonable cheap laboratory where students build models of some problems, and try to answer questions using them. The models are necessarily physical. The degree of finesse that can be achieved is as much a function of creativity as it is of the cost. The kind of equipment available could start as simply as card boards, pins, glue, paper, colours for painting, wires, bread boards, small motors, or even waste material (e.g. broken toys, devices) etc.

This course is conceived as a first course, and hence has no "syllabus" as such. Instead it is a collection of some "simple"/"simplified" problems that should illustrate the nature of M&S. The key to the success is in grasp on M&S that a student achieves, and should answer basic questions like:

1. What aspect/s of the reality does the model capture? What aspect/s does it **not** capture?
2. What questions can the model answer and what questions can it not answer? Why?
3. Is the model capable of simulation?
4. What questions need a simulation using the model to be answered? Are they different from questions that the model can answer without simulation? If so, in what way?
5. ...
6. Get introduced to M&S through actual experience.
7. What tools (mathematical, statistical, programmatic) are required to address problems in a particular stream?

Syllabus. This is an open-ended course, and the instructor is the best judge of topics and case studies to use to convey the spirit of M&S. At the discretion of the instructor, the selection case studies may include:

1. Study of internal combustion engines
2. Study of a plant cell or animal cell
3. Study of planetary motion of our solar system
4. Study of Newton's Laws of motion (various: e.g. central force, projectiles etc.)
5. Study of equilibrium in chemical reactions
6. Study of mechanical adding machines

Suggested Texts/References. No specific texts or references. Instructor can choose any appropriate selection of texts and references.

Notes on Pedagogy. The main thrust of this course should be to make students comfortable in applying their current knowledge of the modeling techniques to solve a variety of problems. The course may be run by assigning mini-projects to groups of students to generate physical, mathematical, programmatic models and demonstrate their usefulness/inadequacies. The deliverable could be a physical model, a computer program (which is expected to follow basic software development norms) or a proposal based on their study, etc. The exact nature of the deliverable by students and the evaluation methodology is left to the instructor. Hence, there are no prescribed reference books/articles. This course is also a placeholder for the top-down approach to M&S. The students, through case studies, are supposed to understand the need for more detailed study of mathematical, statistical and programmatic tools to understand intricacies of M&S.

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2.13 C201 Complex Analysis

Credits. 2

Prerequisites. None

Dependent Courses. C202 (2.14), E001-1 (3.2)

Attributions. Core; C, T

Rationale, Outlook, Purpose, Objectives, and Goals. Complex analysis is a powerful and widely used area of mathematics with applicability in diverse areas of science and engineering. This foundational course is intended to bring the student at an acceptable level of understanding of complex analysis so that (s)he is able to assimilate related material in advanced courses later on in the programme.

Syllabus.

1. Complex Analytic Functions. Complex Numbers. Polar form of complex numbers, triangle inequality. Curves and regions in the complex plane. Complex function, limit, continuity, derivative. Analytic function. Cauchy-Riemann equations. Laplace's equation. Rational functions, roots, exponential function, trigonometric and hyperbolic functions, logarithm, general power.
2. Complex Integrals. Line integral in the complex plane. Basic properties of the complex line integral. Cauchy's integral theorem. Evaluation of line integrals by indefinite integration. Cauchy's integral formula. Derivatives of an analytic function.
3. Laurent Series. Review of power series and Taylor Series. Convergence. Uniform convergence. Laurent series, analyticity at infinity, zeros and singularities.
4. Complex Integration by Method of Residues. Analytic functions and singularities. Residues, poles, and essential singularities. The residue theorem. Contours. Contour integration and Cauchy residue theorem as techniques for real integration. Principal values of integrals.

Suggested Texts/References.

1. Tristan Needham, *Visual Complex Analysis*. Oxford University Press, 1999.
2. Erwin Kreyszig, *Advanced Engineering Mathematics*. Wiley India, 2014.
3. M. J. Ablowitz and A. S. Fokas, *Complex Variables: Introduction and Applications*. Cambridge University Press, second edition, 2003.
4. Arfken and Weber, *Mathematical Methods for Physicists*. Elsevier, 2005.

Notes on Pedagogy. On pedagogical note, it is important to remember that students will be required to learn the evaluation of inverse integral transforms later in their course work. It would be useful if the instructor motivates the students using this as application. The student should be adequately familiarized with methods particularly useful in evaluating inverse transforms.

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2.14 C202 Transforms

Credits. 3

Prerequisites. C101 (2.2), C102 (2.3), C103 (2.4), C104 (2.5), C109 (2.10)

Dependent Courses. None

Attributions. Core; C, T, L

Rationale, Outlook, Purpose, Objectives, and Goals. Integral and discrete transforms are often useful in transforming a complex problem into a simpler one. Moreover, insights about the system can be obtained through transforms. Needless to say that integral and discrete transforms are vital tools in the modeling and simulation premises. The goal of this course is to introduce students to a few commonly used transforms with substantial emphasis on Fourier transform. A significant computing aspect is also expected. Students should be able to write codes for some of the transforms. Students are also expected to learn to analyze the results of transformed signals through computational platforms such as `matlab/scilab/R`.

Syllabus.

1. Introduction and background. Brief introduction to vector spaces, function spaces and basis sets. Special functions. Function parity. Concepts in complex analysis. Kernel of an integral transform.
2. Fourier series. Periodic functions. Fourier series in trigonometric as well as complex exponent representation. Functions with arbitrary period. Solving differential equations with Fourier series.
3. Fourier transform. Fourier integrals. Fourier sine/cosine transforms. Fourier transform. Inverse Fourier transform. Properties of Fourier transform. Convolution. Applications. Solving differential equations using Fourier transform, Power spectrum and its interpretation.
4. Discrete Fourier transform and fast Fourier transform. Discretization. Sampling. Nyquist sampling. Discrete Fourier transform. Properties. Matrix representation of Discrete Fourier transform. Fast Fourier transform. Comparison.
5. Laplace transform. Laplace transform. Properties. Inverse transform using partial fractions, convolution and complex integration. Applications. Solution of differential equations.
6. Wavelet transform. Limitations of Fourier transform. Introduction to wavelets and family of wavelets. Translations and scaling. Continuous and Discrete wavelet transform. Haar scaling and wavelet functions. Functions spaces. Decomposition using Haar bases. General wavelet system. Daubechies wavelets. Multiresolution analysis. Analysis of output of wavelet transforms.
7. Z-transform. Definition of Z-transform. Properties. Inverse Z-translations using complex integral methods. Difference equations.

Suggested Texts/References.

1. L. C. Andrews and B. K. Shivamoggi, *Integral Transforms for Engineers*. Prentice-Hall of India, 2003.
2. Erwin Kreyszig, *Advanced Engineering Mathematics*. Wiley India, 2014.

3. R. N. Bracewell, *The Fourier transform and its applications*. Tata McGraw-Hill, 2003.
4. L. Devnath and D. Bhatta, *Integral transforms and their applications*. Chapman and Hall/CRC, 2010.
5. K. P. Soman and K. I. Ramchandran, *Insights into wavelets - From theory to practice*. Prentice-Hall India, 2005.
6. Online coursework such as Brad Osgood (Stanford), Alan Oppenheim (MIT), etc.

Notes on Pedagogy. An instructor may choose to alter the order to introduce the transforms. However it is logical to start with Fourier series for periodic function, followed by Fourier transform for non-periodic function. The limitation of Fourier transform to resolve the function in both frequency and time domains leads to use of Wavelet and on the other hand Laplace transform can be viewed as 'generalized' Fourier transform, which takes into account the real part of frequency. Similarly Z-transform can be seen as generalized discrete Fourier transform.

A significant emphasize is expected to be on students developing their own codes for various transforms.

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2.15 C203 Difference Equations

Credits. 2

Prerequisites. C101 (2.2)

Dependent Courses. C106 (2.7)

Attributions. Core; C, T

Rationale, Outlook, Purpose, Objectives, and Goals. This and two sister courses C106 (2.7) and C107 (2.8) aim at developing commonly-used modeling formalisms for describing change.

Syllabus.

1. Definitions of difference equations (ordinary and partial) dependent and independent variables, order and degree, types (linear, quasilinear) elliptic, hyperbolic and parabolic difference equations. Types of side conditions for each.
2. Translation operator and algebraic methods to solve degree one homogeneous and inhomogeneous difference equations. Similarity with ODE methods. Methods using the Z transform.
3. Numerical methods of solution of ordinary difference equations. Examples of usage of data structures and creation of algorithms in this context. Difference equations that result from discretization of differential equations (two examples like Euler stepping and Runge Kutta method).
4. Translation operators for partial difference equations and algebraic methods for solving basic forms of partial difference equations analytically.
5. Numerical methods for partial difference equations, classification as sweeping and stepping methods. Examples of usage of data structures and creation of algorithms in this context. Difference equations that result from discretization of partial difference equations (examples of finite difference method only).
6. Application of difference equations in population dynamics and finance.
7. Introduction to theoretical concepts of stability, oscillation and asymptotic behaviour of difference equations and their solutions.

Suggested Texts/References.

1. Saber N. Elaydi, *Introduction to Difference Equations*. Springer, 1999.
2. Ronald E. Mickens, *Difference Equations*. CRC Press, 1991.
3. Walter C. Kelley and Allan C. Peterson, *Difference Equations: An Introduction with Applications*. Academic Press, 2001.
4. *Mathematical Modelling Through Difference Equations*, Chapter 5, in: J. N. Kapur, *Mathematical Modelling*. New Age International Publishers, 2008.
5. Sui Cun Cheng, *Partial Difference Equations*. Taylor and Francis, 2003.

Notes on Pedagogy.

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2.16 C204 Numerical Computing 1

Credits. 2

Prerequisites. C101 (2.2), C103 (2.4), C104 (2.5), C109 (2.10)

Dependent Courses. C301 (2.20)

Attributions. Core; C, L

Rationale, Outlook, Purpose, Objectives, and Goals. Many modeling formalisms and situations lead to formulations that involve the use of numerical computing, which we define loosely as numerical analysis/mathematics plus a strong hands-on computing component. This course and its sister course C301 (2.20) are intended to cover topics of practical importance that are not covered elsewhere in the curriculum.

Syllabus.

1. Finite-Precision Arithmetic. Computer representations of integers: Properties; overflow and roll-over; endianness. Computer representations of "real" numbers: Fixed-point and floating-point; properties of floating-point numbers and representations (e.g., number and distribution of representable floating-point numbers, overflow and underflow, machine epsilon, minimum and maximum representable number; etc.).
2. The Rounding Error. How elementary arithmetic operations are performed on floating-point numbers. How precision is lost in arithmetic operations such as subtraction. Examples of loss of precision such as in computing roots of a quadratic equation, etc. Analysis of the rounding error for simple computations. Useful strategies for avoiding accumulation of rounding error; e.g., minimize arithmetic operations (e.g., Horner's and other methods for polynomial evaluation), re-arrange computation to avoid subtraction of nearly equal floating-point numbers (e.g., in computing roots of a quadratic equation when $b^2 \approx 4ac$), etc.
3. A User's Perspective on the IEEE 754 Specification. IEEE 754 representations of floating-point types and their characteristics. IEEE 754 specifications for arithmetic operations. Special values: `NaN`, `Inf`, signed zero, etc. Optional: provisions for tracking floating-point exceptions.
4. Roots, Zeros, and Nonlinear Equations in One Variable. Are there any roots anywhere? Examples of root-finding methods. Fixed point iteration, bracketing methods such as bisection, *regula falsi*. Slope methods: Newton-Raphson, Secant. Accelerated Convergence Methods: Aitken's process, Steffensen's and Muller's method.
5. Interpolation. What is interpolation? Polynomial approximation. Polynomial interpolation for derivatives and integration. Newton's form of the interpolation polynomial. The interpolation problem and the vandermonde determinant. The Lagrange form of the interpolation polynomial. Divided differences. The error in polynomial interpolation. Spline interpolation and cubic splines.
6. Approximations. The Minimax approximation problem. Construction of the minimax polynomial. Least-squares and weighted least squares approximations. Solving the least-squares problem: direct and orthogonal polynomial methods.

Suggested Texts/References.

1. David Goldberg, *What Every Computer Scientist Should Know About Floating-Point Numbers*. Computing Surveys, March 1991. http://docs.sun.com/source/806-3568/ncg_goldberg.html
2. Doron Levy, *Introduction to Numerical Analysis*. Unpublished, 2010. http://www.math.umd.edu/~dlevy/books/na.pdf
3. M. T. Heath, *Scientific Computing: An Introductory Survey*. McGraw-Hill, 2002. http://heath.cs.illinois.edu/scicomp/
4. John H. Mathews, *Numerical Methods for Mathematics, Science and Engineering*. Prentice-Hall of India, second edition, 2003.
5. Steven C. Chapra and Raymond P. Canale, *Numerical Methods for Engineers*. Tata McGraw-Hill, third edition, 2000.
6. H. M. Antia, *Numerical Methods for Scientists and Engineers*. Hindusthan Book Agency, second edition, 2002.
7. Kendall E. Atkinson, *An Introduction To Numerical Analysis*. Wiley India, second edition, 2008.

Notes on Pedagogy. This is not intended to be a course on formal numerical analysis per se; the hands-on, computing component needs to be emphasized slightly more, a point-of-view that is consistent with the "concept-over-rigour" viewpoint that is at the heart of this programme. Exercises should involve a mix of paper-and-pencil and computing exercises using any programming language (e.g., `C` together with `GSL`) or computing environment (e.g., `matlab/scilab`, `R`, etc.) that students are familiar with. Modeling contexts in which these numerical methods find their way are left to the discretion of the (expert) instructor.

Contributor/s. Vaishali Shah (https://www.researchgate.net/profile/Vaishali_Shah10)

2.17 C205 Optimization 1

Credits. 2

Prerequisites. C101 (2.2), C103 (2.4), C104 (2.5)

Dependent Courses. C302 (2.21), E001-1 (3.2)

Attributions. Core; C, L

Rationale, Outlook, Purpose, Objectives, and Goals. The ubiquity of optimization formulations in mathematical modeling dictates that a solid background in deterministic optimization methods should be an essential part of a modeler's toolkit.

Syllabus.

1. Preliminaries. Why optimize? A survey of optimization problems and their modeling contexts; system/behaviour → model or formulation as an optimization problem, the objective function, domain of the objective function, applicable optimization methods. Some terminology (with lots of pictures): a minimizer, local and global minima, constrained and unconstrained minimization, convex minimization. Visualization in 2D and 3D: contours, surfaces, isosurfaces; visualization tools. The optimization interface in the Gnu Scientific Library (`GSL`).
2. One Dimension. Derivatives, conditions for extrema, and the Taylor series. Numerical methods without derivatives: general structure, parabolic interpolation (and its connection with the secant method), golden section search, two-point bracketing and bisection, Golden section search and Brent's method. Numerical methods that use derivative information: Newton-Raphson, Davidon's method, Brent with bracketing. How close to a minimum is numerically close enough? Comparison of, and perspective on, 1D methods.
3. Linear Programming and the simplex method.
4. Unconstrained Minimization in More Than One Dimension: Generalities. Partial derivatives and conditions for order-independence. Gradient, Hessian, and directional derivative: properties and interpretation. Taylor expansions in $d = 2$ and in $d = n$. Extrema in N dimensions: necessary conditions for an extremum, extreme values and Taylor expansions, quadratic models, geometry of symmetric bilinear forms, Hessian eigenvalues and eigendirections.
5. Unconstrained Minimization in More Than One Dimension: Methods. Ad hoc methods: a simplex-based method, method of alternating variables. Derivative-free method: Nelder-Mead. Algorithmic structure of commonly-used methods. Steepest descent: rationale, algorithm, and convergence behaviour. Using second-derivative information: Newton method and its convergence behaviour; where and why Newton fails; quasi-Newton methods: rationale and generalities; BFGS and DFP. Direction set methods: basic ideas, Powell's method, conjugate directions and quadratic termination, conjugate gradient method.
6. Constrained Minimization. Equality and bound constraints: general theory. A survey of constrained minimization methods for nonlinear problems.
7. (Optional) Deterministic Global Minimization. Survey of global minimization problems and deterministic global minimization methods. Comparison with stochastic methods.
8. (Optional) L_1 Minimization Basics.

Suggested Texts/References.

1. M. T. Heath, *Scientific Computing: An Introductory Survey*. McGraw-Hill, 2002.. http://heath.cs.illinois.edu/scicomp/
2. John H. Mathews, *Numerical Methods for Mathematics Science and Engineering*. Prentice Hall India, second edition, 2003.
3. R. L. Burden and J. D. Faires, *Numerical Analysis*. Brooks Cole, 2004.
4. Forberg, *Numerical Analysis: A practical approach*. McGraw-Hill, 1979.

Notes on Pedagogy. Hands-on work using either `C+GSL` or through computing platforms such as `MATLAB/Scilab` would be beneficial for the students to understand intricacies of optimization problems.

Contributor/s. Vaishali Shah (https://www.researchgate.net/profile/Vaishali_Shah10)

2.18 C206 Statistical Inference

Credits. 3

Prerequisites. C106 (2.7), C107 (2.8)

Dependent Courses. E003-1 (3.6), E007 (3.12)

Attributions. Core; C, T, L

Rationale, Outlook, Purpose, Objectives, and Goals. Statistical inference is a formalism for reasoning under uncertainty. It is crucial for modeling noisy data, analyzing it, and making inferences from it. In an age where almost every human endeavour is getting data-rich, knowledge of the basics of statistical inference will give an edge to the student. Goals: Good conceptual understanding of the fundamentals of statistical inference, together with the ability to apply them as appropriate; to be able to understand and illustrate formal concepts using simulation.

Syllabus.

1. Overview of Statistical Inference and Learning. Parametric and nonparametric models. Fundamental concepts in inference: point estimation, confidence sets, hypothesis testing.
2. Estimating CDF and Statistical Functionals. The empirical distribution function, properties, confidence band, etc. Statistical functionals. Plug-in estimators for linear statistical functionals.
3. The Bootstrap. Bootstrap variance estimation. Bootstrap confidence intervals.
4. Parametric Inference. Parameter of interest and nuisance parameters. Method of moments (MoM), and properties of MoM estimators. Maximum likelihood (ML) estimation and properties of ML estimators. Multiparameter models. The parametric bootstrap. Role of Assumptions.
5. Hypothesis Testing. Fundamentals of hypothesis testing, type-I and type-II errors, p-values, the Neyman-Pearson lemma, etc. Commonly used tests such as: The Wald test and its connection with confidence interval, Pearson's χ^2 test for multinomial data, the permutation test, the likelihood ratio test, goodness-of-fit tests, t- and F-tests, a few standard tests of normality, correlation test. The multiple testing problem.
6. Bayesian Inference (Optional). The Bayesian philosophy and the Bayesian method. Large sample properties of Bayes procedures. Flat priors, improper priors and "noninformative" priors. Multiparameter problems. Strengths and weaknesses of Bayesian inference *vis a vis* the frequentist/classical approaches.
7. Statistical Decision Theory (Optional). Overview of philosophy, formalism, and methods.

Suggested Texts/References.

- Larry Wasserman, *All of Statistics*. Springer-Verlag, 2004.
- Morris deGroot and Mark Schervish, *Probability and Statistics*. Addison-Wesley, 2002.
- John E. Freund, *Mathematical Statistics*. Prentice-Hall of India, 1998.

Notes on Pedagogy. The emphasis of the course should be on understanding concepts well rather than on mathematical rigour, on being able to interpret formal results and visualize formal constructions, and on being able to apply these concepts and methods to real problems. That said, formal reasoning and analysis should be an integral part of the course wherever it helps understand or illustrate concepts better. The course should also develop a perspective on real-life data modeling contexts where statistical inference plays a crucial role. Hands-on computational work using `R` should be used liberally as a means to illustrate (by the instructor) or understand (by the student) concepts, methods, and applications.

Contributor/s. Mihir Arjunwadkar (`http://cms.unipune.ac.in/~mihir`)

2.19 C207 M&S Hands-On 2

Credits. 5

Prerequisites. C111 (2.12)

Dependent Courses. C304 (2.23), C305 (2.24)

Attributions. Core; C, L, S

Rationale, Outlook, Purpose, Objectives, and Goals. Same as that for the sister course C111 (2.12).

Syllabus. This is an open-ended course, and the instructor is the best judge of topics and case studies to use to convey the spirit of M&S. At the discretion of the instructor, appropriate models could be studied for systems such as:

1. Economic systems (share trading/insurance/banking, etc.)
2. Socio-political systems (social migrations, Bureaucratic Structure and Performance, Electoral Politics and Political Participation, etc.)
3. Water bodies, rains, dams and floods, how the water level would rise/recede, tidal waves, tsunami, etc.
4. Flow of micro-fluidic doses through blood plasma
5. Electrical/Electronic control system, medical instruments
6. Artificial intelligence systems like sound, vision detection, decision making, sensing, etc.
7. Biological systems: evolution, reproduction, self-defence, carbon-cycle related models

Suggested Texts/References. No specific texts or references. Instructor can choose any appropriate selection of texts and references.

Notes on Pedagogy. This course is to be pitched at a level little higher than the sister course C111 (2.12). This may be achieved by assigning, say, group projects as part of C111 (2.12) and projects for individual or pairs in this course. The aim of this course is to make students realize the nuances of modeling, choice of simulation methods and obtaining useful results through M&S. The students should also be able to take a decision on which tools/subjects should be studied in depth.

Contributor/s. Abhijat Vichare (https://www.linkedin.com/pub/abhijat-vichare/2/822/828), Bhalchandra Gore (http://cms.unipune.ac.in/~bwgore), Abhay Parvate (https://jp.linkedin.com/in/abhay-parvate-5b808250)

2.20 C301 Numerical Computing 2

Credits. 3

Prerequisites. C202 (2.14)

Dependent Courses. None

Attributions. Core; C, L

Rationale, Outlook, Purpose, Objectives, and Goals. Many modeling formalisms and situations lead to formulations that involve the use of numerical computing, which we define loosely as numerical analysis/mathematics plus a strong hands-on computing component. This course and its sister course C202 (2.14) are intended to cover topics of practical importance that are not covered elsewhere in the curriculum.

Syllabus.

1. Numerical Differentiation. Basic concepts. Differentiation via interpolation. The method of undetermined coefficients. Numerical derivatives using forward difference, backward difference and central difference. Richardson extrapolation. Differentiation using Lagrange Polynomial, Newton Polynomial.
2. Numerical Integration. Basic concepts. Integration via interpolation. Composite integration rules. Additional integration techniques. The method of undetermined coefficients. Change of an interval. General integration formulas. Simpson integration. The quadrature error. Composite Simpson rule. Gaussian quadrature. Maximizing the quadrature's accuracy. Convergence and error analysis. Romberg integration. Adaptive quadrature basics.
3. Numerical Linear Algebra Using Software Tools. Quick working introduction to `BLAS/LAPACK`, and appropriate interfaces in `GSL`, `MATLAB/Scilab`, etc.
4. Solution of linear systems. Gaussian elimination. Pivoting. Ill-conditioning. Gauss-Jordan method. Matrix inversion. Triangular factorization (LU). Permutation matrices. Cholesky factorization. Iterative methods for linear systems. Diagonally dominant matrices. Jacobi iteration. Gauss-Seidel iteration. Convergence.
5. Eigenvalues and Eigenvectors Homogeneous systems, Power Method, Jacobi's method, Given's, Householder's transformation and Lanczos transformation to tridiagonal form, LR, QL/QR transformation for eigenvalues of tridiagonal matrices, determinants of tridiagonal matrices, Strum sequences, symmetric matrices, band matrices

Suggested Texts/References.

1. H. M. Antia, *Numerical Methods for Scientists and Engineers*. Hindusthan Book Agency, second edition, 2002.
2. Doron Levy, *Introduction to Numerical Analysis*. Unpublised, 2010.. `http://www.math.umd.edu/~dlevy/books/na.pdf`
3. M. T. Heath, *Scientific Computing: An Introductory Survey*. McGraw-Hill, 2002.. `http://heath.cs.illinois.edu/scicomp/`
4. John H. Mathews, *Numerical Methods for Mathematics, Science and Engineering*. Prentice Hall of India, second edition 2003.

5. D. V. Griffiths and I. M. Smith, *Numerical Methods for Engineers*. Chapman and Hall/CRC, second edition 2011.
6. Steven C. Chapra and Raymond P. Canale, *Numerical Methods for Engineers*. Tata McGraw-Hill, second edition 2000.
7. Curtis F. Gerald and Patrick O. Wheatley, *Applied Numerical Analysis*. Addison-Wesley, fifth edition 1998.
8. Kendall E. Atkinson, *An Introduction To Numerical Analysis*. Wiley India, second edition, 2008.

Notes on Pedagogy. This is not intended to be a course on formal numerical analysis per se; the hands-on, computing component needs to be emphasized slightly more, a point-of-view that is consistent with the "concept-over-rigour" viewpoint that is at the heart of this programme. Exercises should involve a mix of paper-and-pencil and computing exercises using any programming language (e.g., `C`) or computing environment (e.g., `matlab/Scilab`, `R`, etc.) that students are familiar with. Modeling contexts in which these numerical methods find their way are left to the discretion of the (expert) instructor. Coding numerical methods oneself helps most students understand these methods better. The same codes can later on be uses for learning high-performance and parallel computing.

Contributor/s. Vaishali Shah (`https://www.researchgate.net/profile/Vaishali_Shah10`)

2.21 C302 Optimization 2

Credits. 3

Prerequisites. C106 (2.7), C205 (2.17)

Dependent Courses. None

Attributions. Core; C, L

Rationale, Outlook, Purpose, Objectives, and Goals. Stochastic optimization methods often fare better in situations involving objective functions with multiple local or global minima, when there is combinatorial complexity in the optimization problem, when the goal is to locate a global minimum, and when the measurement or computation of the objective function itself involves uncertainties. A background in these methods should be an essential part of a modeler's toolkit.

Syllabus.

1. Introduction. Formal problem statement. Stochastic vs. deterministic optimization. Principles of stochastic optimization. Local vs. global minimization. An overview of problems involving multiple minima, local or global.
2. Random Search. General properties of direct random search. A few specific algorithms for random search.
3. Stochastic Approximation. Finite-difference SA. Simultaneous perturbation SA.
4. Simulated Annealing. The analogy between optimization and free-energy minimization by a physical system. The travelling salesman problem and SA.
5. Genetic Algorithms. Introduction. Chromosome coding and the basic GA operations. The core genetic algorithm. Implementation aspects. Some perspective on the theory for GAs.
6. More Bio-Inspired Algorithms. Overview of ant-colony and swarm optimization methods.

Suggested Texts/References.

1. James C. Spall, *Stochastic Optimization*, in J. Gentle, W. Härdle, and Y. Mori, eds., *Handbook of Computational Statistics*. Springer, 2004.
2. James C. Spall, *Introduction to Stochastic Search and Optimization: Estimation, Simulation, and Control*. Wiley, 2003.
3. M. Michell, *An Introduction to Genetic Algorithms*. MIT Press, 1996.
4. P. J. M. Van Laarhoven and E. H. L. Aarts, *Simulated Annealing: Theory and Applications*. Kluwer Academic Publishers, 1987.

Notes on Pedagogy. The syllabus outline above is partially based on the first review article above; a qualified instructor experienced in stochastic optimization methods may alter the sequence or topics without altering the overall focus of the course. Methods in a similar vein, such as ant-colony and swarm optimization methods, may be included at the instructor's discretion. This course has some overlap with the concurrently-run course C304 (2.23). Ideally, instructors for the two courses should coordinate the delivery of their respective content so that a coherent perspective emerges in the end.

Contributor/s. Mihir Arjunwadkar (http://cms.unipune.ac.in/~mihir)

2.22 C303 Stochastic Simulation

Credits. 3

Prerequisites. C106 (2.7), C107 (2.8), C110 (2.11)

Dependent Courses. None

Attributions. Core; C, T, L

Rationale, Outlook, Purpose, Objectives, and Goals. To familiarize the student with simulation methods (together with their modeling contexts) involving the use of randomness, including methods for sampling from probability distributions, Monte Carlo integration, Markov chain Monte Carlo methods, etc.

Syllabus.

1. Randomness. Randomness in natural processes: decaying nuclei, chaotic oscillators, leaky faucets, cosmic ray showers, etc. Randomness as complexity, non-compressibility of information, unpredictability, ignorance, statistical independence. Randomness as a modeling assumption. Randomness and entropy.
2. Pseudo-Random Number Generators. Generating deterministic sequences of numbers that appear random. Uniform pseudo-random number generators their properties. Breaking correlations via shuffling. Mersenne Twister and other state-of-the-art generators: an overview. Simple transformations from the Uniform. Other distributions as transformations from the Uniform: exponential, Cauchy, Beta, etc. $N(0,1)$ using Box-Müller and other methods. Arbitrary distributions and acceptance-rejection sampling. Testing for randomness: how random is random enough? `DIEHARD` and other test batteries.
3. (Optional) Correlated Random Numbers. Normal random numbers with pre-specified correlations. Nataf transformation.
4. Monte Carlo Integration. Estimating π using a dartboard. Estimating one-dimensional integrals: basic MC integration. Importance sampling for better estimators and tighter errorbars. Deterministic vs. Stochastic: Behaviour of the error as function of the number of dimensions.
5. Sampling and Integration in More Than One Dimension. Markov chains, their properties, and limit theorems. Metropolis, Metropolis-Hastings and Gibbs sampling. Master equation, detailed balance, and why Metropolis-Hastings works. Relationship between Metropolis-Hastings, Metropolis, and Gibbs. Relationship between Metropolis and rejection sampling. A survey of illustrative problems involving high-dimensional distributions, integration/expectation, and simulations. Practical considerations: the adjustable step length parameter, behaviour of Markov chain Monte Carlo methods when the distribution being sampled is multimodal, burn-in or equilibration behaviour, detecting equilibration/convergence of the Markov chain, convergence diagnostics, correlations and error bars on estimates, etc.
6. (Optional) Specialized (M&)S Methods Involving Randomness. Reaction kinetics, epidemiology, and population dynamics: The Gillespie method. Agent-based stochastic models in epidemiology and other fields. Tutorial on stochastic differential equations. Discrete versus continuous, stochastic versus deterministic: What is more appropriate/useful for given problem?

Suggested Texts/References.

1. Charles M. Grinstead and J. Laurie Snell, *Introduction to Probability*. American Mathematical Society, 1997 or later. https://math.dartmouth.edu/~prob/prob/prob.pdf
2. Hoel, Port, and Stone, *Introduction to Stochastic Processes*. Houghton Mifflin, 1972.
3. George Casella and Edward I. George, *Explaining the Gibbs Sampler*, The American Statistician **46**(3) 167–174 (1992).
4. Brooks, Gelman, Jones, and Meng (eds.), *Handbook of Markov Chain Monte Carlo*. Chapman and Hall/CRC, 2011.
5. Liang, Liu, and Carrol, *Advanced Markov Chain Monte Carlo Methods: Learning from Past Samples*. Wiley, 2010.
6. Gilks, Richardson, and Spiegelhalter, *Markov Chain Monte Carlo Methods in Practice*. Chapman and Hall, 1996.

Notes on Pedagogy. This syllabus is based on an outline for a longer course that was refined over several course deliveries by the contributor (see below). Depending on the background and capabilities of the students, this outline may need to be somewhat diluted or intensified – without compromising upon the essential content and the goals for the course. This course needs sufficient level of hands-on activities, and students require adequate computing skills. What is not mentioned explicitly in the syllabus is the modeling contexts in which stochastic methods can be useful. Exposing the student to such modeling contexts is a must. Specific modeling contexts can be chosen by the instructor according to her/his field of specialization.

Contributor/s. Mihir Arjunwadkar (http://cms.unipune.ac.in/~mihir)

2.23 C304 M&S Overview

Credits. 4

Prerequisites. C207 (2.19)

Dependent Courses. C401 (2.25)

Attributions. Core; C, L, S

Rationale, Outlook, Purpose, Objectives, and Goals. This course, together with sister courses C111 (2.12) and C207 (2.19), are expected to strike a balance between generalities and specific examples, between stochastic and deterministic models, and between describing finished work and actual hands-on modeling on the part of a student. The group of courses C111 (2.12), C207 (2.19), C304 (2.23), and C305 (2.24) are the heart of this programme, as they attempt to put the diversity of topics in the curriculum in a unified perspective. They are expected to convey the spirit of mathematical modeling in a coherent manner, through a proper mix of discussion of principles with aptly chosen case-studies from diverse fields, thus putting the methodological training of the rest curriculum in a unified perspective.

Syllabus.

- Foundations of M&S. Modeling, Simulation, M&S as a newly evolved discipline of study, The multidisciplinary nature of M&S; Basic concepts, terms and their definitions; Types of models (mathematical, numerical, statistical, physical, finite element, finite volume, finite domain time difference (FDTD), data-based, agent based, etc.); Actual system and its model: what to expect.
- M&S Characteristics and Descriptors. M&S paradigms–continuous, sampled, event-based, etc.; Attributes–sensitivity, constraints, resolution/granularity, etc.; Verification, Validation and Accreditation of models.
- Classification of models. Classifications based on nature of realization of the model–physical, mathematical, statistical, graphical, etc.; classification based on nature of equation, nature of control parameters and output parameters; contrasting pairs like continuous/discrete, linear/non-linear, deterministic/stochastic, real-time/batch, static/dynamic, time varying/steady state, etc.;
- M&S Process Cycle. model phase, code phase, execution phase, analysis phase, testing, verification and validation phase; feedback mechanism for improvements, quality assurance
- Tools Required for M&S Mathematical, Statistical, Numerical, Programmatic; The need to learn all of them; their use and estimating the nature of final outcome
- Case Studies. Various M&S case studies to bring out the connections between the topics learned and their applications may be chosen. Given the diversity of the M&S enterprise, these are expected to be pedagogically most demanding and a challenge to the instructor.

Suggested Texts/References.

- J. A. Sokolowski and C. M. Banks (Ed.), *Modeling and Simulation Fundamentals.* Wiley, 2010.
- B. P. Zeigler, Herbert Praehofer and Tag Gon Kim, *Theory of Modeling and Simulation.* Academic Press India, 2000.
- A. M. Law, *Simulation, Modeling & Analysis.* McGraw-Hill Education, 2014.

- P. Saxena, *Modeling and Simulation*. Narosa, 2014.
- J. N. Kapur, *Mathematical Modelling*. New Age International Publishers, 2015.

Notes on Pedagogy.

Contributor/s. Bhalchandra Gore (`http://cms.unipune.ac.in/~bwgore`), Sukratu Barve (`http://cms.unipune.ac.in/~sukratu`)

2.24 C305 M&S Apprenticeship

Credits. 2

Prerequisites. C207 (2.19). In principle, all courses from the first two semesters.

Dependent Courses. C401 (2.25)

Attributions. Core; C, L, S

Rationale, Outlook, Purpose, Objectives, and Goals. This is an individualized course where a student is to work closely with a mentor. The emphasis of this course is on developing problem-solving, self-learning/self-study, and presentation (written and oral) skills. With the help of the mentor, the student should carry out hands-on work related to the broad focus of the programme, and culminating into a written report and a presentation. With their internship C401 (2.25) on the horizon, this course is intended to prepare students to develop appropriate skills including but not limited to literature search, resourcefulness, hands-on problem-solving related to a topic not studied before, etc. See pedagogic notes below.

Syllabus. No fixed syllabus. Mentor to decide the best strategy to achieve aims and objectives of this course for each student separately.

Suggested Texts/References. No prescribed texts. The mentor and the student can use any text or reference individually depending on the topic of study.

Notes on Pedagogy. The role of the mentors is crucial for the success of this course. If a student has already decided her/his place of internship C401 (2.25), advisor, topic, etc., then the mentor should make sure, in collaboration with the organization or advisor for the internship, that (s)he spends her/his time in developing skills and background necessary for the internship. For other students, and until the details of their internship are not finalized, mentor should work on developing students' self-study, presentation (written and oral), and any other skills that may not be covered adequately elsewhere during the programme, or those in which the student may not be adequately trained. Assigning a modeling project can be one possible strategy to achieve the goals of this course. The mentor and the students need to meet on regular basis to ensure good and regular progress.

Contributor/s. Bhalchandra Pujari (`http://cms.unipune.ac.in/~bspujari`), Mihir Arjunwadkar (`http://cms.unipune.ac.in/~mihir`)

2.25 C401 Internship

Credits. 25

Prerequisites. C305 (2.24)

Dependent Courses. None

Attributions. Core; L, S

Rationale, Outlook, Purpose, Objectives, and Goals. Internship is the pinnacle of the Master of Technology (M.Tech.) Programme in Modeling and Simulation. The purpose of the internship is for the students to get in-depth exposure and experience in addressing challenging, real-life problems through M&S methods.

Syllabus. No fixed syllabus. Internship advisor/s and internal mentor/s at the Centre to decide the best strategy to achieve the aims and objectives of the internship for each student separately.

Suggested Texts/References. No prescribed texts.

Notes on Pedagogy. Internships are intended to be individual, and spanning a complete semester. In the best interest of the student, internships in settings external to the Centre (such as industry, research or academic institutes, NGOs, etc., depending on the interests of the student) are recommended, although possibilities of in-house internships are not ruled out. The internship topic/project may span any breadth of the M&S enterprise in any problem domain, from translating a domain-specific problem into an appropriate mathematical model, attempting to get analytical insights into the behaviour of the model, to exploring the behaviour of the model through computing/simulation. While the internship may have a substantial computing/coding component, it is not intended to be a pure software/coding project. The Centre's faculty committee is the supreme authority of all matters relating to the approval of internship topics/projects. The M&S context of the topic/project should be well-understood by the student, and should be brought out clearly in the report and presentations. The student, the external advisor/s, and the student's mentor/s at the Centre should ensure this, and have clarity as to where the internship fits into the M&S enterprise. Evaluation for this course is to be done on the basis of (a) regular reporting by the student to the external advisor/s and the internal mentor/s, (b) one or more mid-term presentations, (c) a final presentation, and (d) a final report.

Contributor/s. Charulata Patil (`charulata@cms.unipune.ac.in`), Mihir Arjunwadkar (`http://cms.unipune.ac.in/~mihir`)

3 Choice-Based Credits: In-House Electives

3.1 Structure of the Choice-Based Curriculum

Semester 2

Choice-based/elective credits: 7 (to go with 18 core credits)

Code (Section)	Course Name	Credits
E001-1 (3.2)	Digital Signal and Image Processing 1	5
E002-1 (3.4)	Computational Fluid Dynamics 1	5
E003-1 (3.6)	Machine Learning 1	5
E004-1 (3.8)	Operations Research 1	5

Semester 3

Choice-based/elective credits: 10 (to go with 10 core credits)

Code (Section)	Course Name	Credits
E001-2 (3.3)	Digital Signal and Image Processing 2	5
E002-2 (3.5)	Computational Fluid Dynamics 2	5
E003-2 (3.7)	Machine Learning 2	5
E004-2 (3.9)	Operations Research 2	5

Semester 2 or 3

The following standalone choice-based courses (i.e., do not have another choice-based course as a prerequisite) can be floated during semester 2 or 3, depending on enrollment and availability of instructors.

Code (Section)	Course Name	Credits
E005 (3.10)	Concurrent Computing	5
E006 (3.11)	High-Performance Computing	5
E007 (3.12)	Advanced Data Analysis	2
E008 (3.13)	Computing with `Java`	2
E009 (3.14)	Theory of Computation	5
E010 (3.15)	Functional Programming	2
E011 (3.16)	Computing with `Python`	2

3.2 E001-1 Digital Signal and Image Processing 1

Credits. 5

Prerequisites. C101 (2.2), C102 (2.3), C103 (2.4), C104 (2.5), C203 (2.15) or equivalent, or as defined by the instructor/s

Dependent Courses. E001-2 (3.3)

Attributions. CBC; C, T, L, S

Rationale, Outlook, Purpose, Objectives, and Goals. To introduce student to signal modeling and analysis tools, domain-specific formalisms and techniques, and their applications to solve real-life problems in various fields like electronic communication, signal detection, satellite imaging, medical diagnostic signals and images, video analysis, etc. To make student aware of (a) basic theory and mathematical, statistical and algorithmic tools (b) perspective on modeling by way of real-life contexts, examples and applications, and (c) relevant numerical methods. Specific goals of this course are: Understanding the need for signal processing; understanding the correspondence between actual devices, their operations, and their mathematical-statistical representations; learning mathematical, statistical, and algorithmic tools used to improve the quality of a signal and extract useful information from signal; being able to design simple systems for signal processing (like digital filters, digital spectrum analyzer, etc.) using tools such as transforms (Fourier, Z, wavelet), difference equations, pole-zero and frequency plots, mean, median, variance, histogram, probability distributions, etc.; being able to analyze given signal using appropriate tools and infer about quality, content, etc.

Syllabus.

1. Discrete time signals: sequences; representation of signals on orthogonal basis; sampling and quantization; reconstruction of signals; Nyquist's theorem; analog $\rightleftharpoons$ digital signal conversions.
2. Discrete systems: attributes, classifications, analysis of LTI systems, representation of discrete time systems using difference equations, implementation of discrete time systems; correlation of discrete time signals.
3. Z-transform, frequency analysis, discrete Fourier transform (DFT), fast Fourier transform algorithm, frequency response of a system, spectra at output of LTI system; convolution-deconvolution concepts.
4. LTI system as frequency domain filters; filter characterization, inverse systems.
5. Design of FIR and IIR filters; Gaussian, Butterworth, Chebyshev approximations; low-pass, high-pass, notch, bandpass and band-reject filters; effect of quantization on filters– round-off effects.
6. Adaptive filters; power spectrum estimation.
7. Applications of DSP to speech/music and radar/radio-telescope signal processing.

Suggested Texts/References.

1. J. G. Proakis and D. G. Manolakis, *Digital Signal Processing Principles, Algorithms, and Applications*. Pearson, 2012.
2. Oppenheim and Schafer, *Digital Signal Processing*. PHI Learning, 2008.

Notes on Pedagogy. At the discretion of the instructor, `matlab/octave/scilab` can be used for computing. This has the advantage of letting a student focus more on the domain context rather than on programming.

Contributor/s. Bhalchandra Gore (`http://cms.unipune.ac.in/~bwgore`)

3.3 E001-2 Digital Signal and Image Processing 2

Credits. 5

Prerequisites. E001-1 (3.2) or equivalent, or as defined by the instructor/s

Dependent Courses. None

Attributions. CBC; C, T, L, S

Rationale, Outlook, Purpose, Objectives, and Goals. See purpose/outlook/rationale/goals for the sister course E001-1 (3.2). The focus of this follow-up course is more on digital image processing; e.g., electronic communication, satellite imaging, medical diagnostic images, video analysis, image segmentation, etc. Specific goals of this course are: Understanding the need for image processing; understanding the correspondence between actual devices (camera, X-ray, tomographic devices, etc.), their operations, and their mathematical-statistical representations; learning mathematical, statistical, and algorithmic tools used to improve quality of image and extract useful information from image; being able to design simple systems for image processing (like image smoothing, removal of noise, color spectrum analysis etc.) using tools like mean, median, variance, histogram, probability distribution, spatial and temporal filters, etc.; being able to analyze given image using appropriate tools and infer about quality, content, etc.; learning to segment the given image to isolate different objects from it.

Syllabus.

1. What is digital image processing? Its origin, overview of fields of applications, fundamental steps in digital image processing,components of an image processing system.
2. Digital image fundamentals: Human eye and image formation; EM spectrum, image sensing and acquisition, sampling and quantization, basic relationships among pixels-neighbours, connectivity, regions, boundaries, distance measures.
3. Tools used for digital image processing: matrices and vectors, linear vs. non-linear operations, set and logical operators, image transforms, probabilistic methods.
4. Intensity transformations. Basic functions: negation, log, gamma transformation, histogram processing.
5. Spatial filtering: fundamentals, smoothing and sharpening spatial filters, unsharp masking and highboost filtering, use of gradients for non-linear image sharpening, Laplacian operator, using fuzzy techniques for spatial filtering and for intensity transformations
6. Filtering in frequency domain: Fourier series and transform, DFT, FFT, generalization for 2D image space, basic filtering in frequency domain, correspondence between spatial and frequency domain filtering, image smoothing and sharpening using frequency filters, low-pass, high-pass and band-pass filters, notch and band-reject filters, Gaussian, Butterworth, Laplacian filters.
7. Image restoration and reconstruction: Image degradation model, modeling noise, noise reduction using spatial filtering, periodic noise reduction using frequency domain filtering, estimating image degradation function using observation, experimentation and modeling; inverse filtering, statistical (Wiener's mean square error filtering, constrained least square filtering, mean filtering (arithmetic, geometric and harmonic); image restoration from projections (fundamentals of tomography).
8. Colour image processing; colour models: RGB, CMY, CMYK, HSI, relations between them; colour transformations, colour smoothing and sharpening.

9. Wavelets: Haar, Daubechies; DWT, 2D generalization, significance of wavelet coefficients, compression using wavelets.
10. Image compression techniques: spatial and temporal redundancy in images, fidelity criteria, image compression models, some image compression methods (using Huffman, Golomb, arithmetic, LZW, run-length, bit-plane and block-transform coding), relation between block-transform coding and wavelets.
11. Image segmentation fundamentals; point, line and edge detection, thresholding, region-based segmentation.
12. Overview of topics like Video analysis, morphology, watermarking, object/pattern recognition, compressed sensing, etc.

Suggested Texts/References.

1. R. C. Gonzalez and R. E. Woods, *Digital Image Processing, Third Edition.* Pearson, 2013.
2. Bose and Tamal, *Digital Signal and Image Processing.* Wiley India, 2008.

Notes on Pedagogy. At the discretion of the instructor, the computer vision library `OpenCV` can be introduced and used profusely in addition to `matlab/octave/scilab` to ease the programming effort, allowing a student to focus on the formalism and the domain context.

Contributor/s. Bhalchandra Gore (`http://cms.unipune.ac.in/~bwgore`)

3.4 E002-1 Computational Fluid Dynamics 1

Credits. 5

Prerequisites. As defined by the instructor/s

Dependent Courses. E002-2 (3.5)

Attributions. CBC; C, T, L, S

Rationale, Outlook, Purpose, Objectives, and Goals. Develop intermediate-level understanding and hands-on skills in the domain of computational fluid dynamics.

Syllabus.

1. Elementary Concepts. Background space, coordinate systems. Fields, scalars, vectors, tensors, transformations, distance metric. Concepts of vector calculus (flux, line integral, Gauss and Stokes theorems). Index notation and Einstein convention. Total derivative, integral curves, velocity field and co-moving derivative.
2. Balance Equations. Equation of continuity. Jacobians and their rates of change. Lagrangian coordinates. Reynolds theorem. Surface forces and traction vector. Cauchy theorem and concept of stress tensor. Cauchy equation of momentum balance. Angular momentum balance equation. Heat flux density, internal energy density, energy balance equation.
3. Constitutive Relations. Introduction. Thermodynamic stimulus and response, rate of response. Darcy's, Fourier's, Ohm's and Fick's laws, Hooke's law, Newton's law of viscosity. Shear, rotation and dilation of velocity field, Navier-Stokes equation, boundary conditions and their importance.
4. Examples of Flow. Hagen-Poisseuille flow, Couette flow and other special cases.

Suggested Texts/References.

1. T. J. Chung, *Computational Fluid Dynamics*. Cambridge University Press, 2002.

Notes on Pedagogy.

Contributor/s. Sukratu Barve (http://cms.unipune.ac.in/~sukratu)

3.5 E002-2 Computational Fluid Dynamics 2

Credits. 5

Prerequisites. E002-1 (3.4) or equivalent, or as defined by the instructor/s

Dependent Courses. None

Attributions. CBC; C, T, L, S

Rationale, Outlook, Purpose, Objectives, and Goals. Develop intermediate-level understanding and hands-on skills in the domain of computational fluid dynamics.

Syllabus.

1. FEM Techniques. Finite elements. Shape functions. Finite element interpolation functions. Weighted residual approach. Assembly of element equation. Finite element formulation for advection equation.
2. Finite Volume Approach. Finite volume method. Finite volume discretization. Face area and cell volume. Finite volume via finite difference. Finite volume via finite element method. Comparison of finite difference, finite element, and finite volume methods.
3. Grid Generation. Structured grid generation. Unstructured grid generation. Mesh adaptation. Automatic grid generation for complex geometry problems. Computing techniques.
4. Application to Multiphase Flows.
5. Higher-Order Methods for CFD.
6. Optimization Through CFD. Optimization problem associated with evaluation of first derivative. Optimization problem associated with evaluation of second derivatives.
7. Advanced Fluid Dynamics. Intermediate structures like vortices, boundary layers, shocks, waves and caustics, stream filaments.
8. Numerical Methods. Grid generation techniques for structures and unstructured grids.
9. Hands-On Problem-Solving Through CFD. Implementation of codes for CFD. Computational environments for CFD such as `OpenFOAM, CFDExpert`. `OpenFOAM` architecture, solvers cases and utilities; writing cases and solvers. `CFDEXpert` problems.

Suggested Texts/References.

1. T. J. Chung, *Computational Fluid Dynamics*. Cambridge University Press, 2002.

Notes on Pedagogy.

Contributor/s. Sukratu Barve (`http://cms.unipune.ac.in/~sukratu`)

3.6 E003-1 Machine Learning 1

Credits. 5

Prerequisites. C206 (2.18) or equivalent, or as defined by the instructor/s

Dependent Courses. E003-2 (3.7)

Attributions. CBC; C, T, L, S

Rationale, Outlook, Purpose, Objectives, and Goals. In the current era of data explosion, scientists and engineers are looking for methods to extract relevant information through automation. Machine learning methods enable development of algorithms to "learn" from the data and make relevant inferences and predictions. This course is designed to introduce students with the subject of machine learning via a variety of statistical tools like classification, clustering, etc. At the end of the course, students are expected to understand the basics of classification and clustering, develop necessary codes, and make correct inferences from given data.

Syllabus.

1. Introduction and Background. What is machine learning? Overview and survey of applications. Problem of induction and statistical inference: Input-output functions, Boolean functions, parametric and non-parametric inference. Probability, certainty, and Bayes theorem. Introduction to typical learning tasks: regression, pattern recognition, feature selection, classification, clustering, rule induction (association). Model validation techniques: cross validation, leave-one-out, majority, etc. Measures of performance of a classifier: confusion matrix, sensitivity, specificity, ROC curves and the AUC, etc.
2. Computational Environments for Machine Learning. Setting up of modeling frameworks (`Weka` and `R`), I/O formats, basic introduction to interfaces.
3. Supervised Learning. Additive models, generative models and discriminative models, logistic regression, Naïve Bayes classifier, linear discriminant analysis, neural networks and support vector machines.
4. Unsupervised Learning fundamentals. Clustering: k-means, hierarchical, self-organizing map. Feature selection via principal component analysis.
5. Laboratory. Models using `Weka` or `R` on UCI benchmark data sets. Writing interfaces for a classifier as derived from a learner. Regression Models. k-means clustering, writing interface for a clusterer.

Suggested Texts/References.

1. T. Hastie, R. Tibshirani, J. H. Friedman, *The Elements of Statistical Learning: Data Mining, Inference, and Prediction*. Springer, 2013.
2. Tom Mitchell, *Machine Learning*. McGraw-Hill, 1997.
3. Peter Flach, *Machine Learning: The Art and Science of Algorithms that Make Sense of Data*. Cambridge University Press, 2012.
4. Carl Edward Rasmussen and Christopher K. I. Williams, *Gaussian Processes for Machine Learning*. MIT Press, 2005.
5. Daphne Koller and N. Friedman, *Probabilistic Graphical Models: Principles and Techniques*. MIT Press, 2009.

6. Christopher Bishop, *Pattern Recognition and Machine Learning*. Springer, 2007.
7. Kevin P. Murphy, *Machine Learning: A Probabilistic Perspective*. MIT Press, 2012.
8. Larry Wasserman, *All of Statistics: A Concise Course in Statistical Inference*. Springer, 2004.
9. David MacKay, *Information Theory, Inference and Learning Algorithms*. Cambridge University Press, 2003.
10. Y. S. Abu-Mostafa, Malik Magdon-Ismail, and Hsuan-Tien Lin, *Learning From Data*. AMLBook, 2012.
11. Mehryar Mohri, Afshin Rostamizadeh, and Ameet Talwalkar, *Foundations of Machine Learning*. MIT Press, 2012.

Notes on Pedagogy. Websites such as http://kaggle.com/ offer challenges based on machine learning. Instructors are encouraged to involve students in such competitions. Organizational, administrative, and infrastructural assistance required for such participation should be provided by the Centre.

Contributor/s. V. K. Jayaraman (https://in.linkedin.com/in/jayaraman-valadi-a7916925)

3.7 E003-2 Machine Learning 2

Credits. 5

Prerequisites. E003-1 (3.6) or equivalent, or as defined by the instructor/s

Dependent Courses. None

Attributions. CBC; C, T, L, S

Rationale, Outlook, Purpose, Objectives, and Goals. Students are expected to be familiar with basic tools of machine learning by now. This course should be pitched at slightly advanced level than the first course E003-1 (3.6). At the end of this course, students are expected to be able to develop new hybrid algorithms for data analysis and predictions. Students may be introduced to standalone software packages that employ machine learning tools.

Syllabus.

1. Formulation of the Learning Problem. Learning as a statistical problem: estimation of probability measure and basic problems of statistics, learning as density estimation, risk, empirical risk and structural risk, introduction to ill-posed problems and regularization. Learning as an algebraic problem. Learning as a computational problem: learnability, PAC learning, bounds on data, algorithmic learning theory basics. Laboratory: linear models in `R`, writing basic interface for a learner.
2. Reinforcement Learning.
3. Ensemble Methods. Boosting and Bagging.
4. Intelligent Agents.
5. Advanced Clustering Methods. Gaussian/Normal mixture models and the EM algorithm. Fuzzy clustering.
6. Feature Selection. Feature selection using singular value decomposition (SVD). Various filter and wrapper methods.
7. Advanced Applications, Machine Learning Algorithms, and Case Studies. The machine learning approach to time series analysis. Fundamentals and application of clustering/classification to image analysis. Text analytics and natural language processing fundamentals with applications. Social media analytics. Financial analytics.
8. Laboratory: Case studies based on the topics covered. Competitions from `kaggle.com` and similar platforms.

Suggested Texts/References. See the **Suggested Texts/References** section for the sister course E003-1 (3.6).

Notes on Pedagogy. Websites such as `kaggle.com` offer rich data sets and challenges for exercising machine learning skills and expertise. Instructors are encouraged to involve students in such competitions. Organizational, administrative, and infrastructural assistance required for such participation should be provided by the Centre.

Contributor/s. V. K. Jayaraman (`https://in.linkedin.com/in/jayaraman-valadi-a7916925`)

3.8 E004-1 Operations Research 1

Credits. 5

Prerequisites. C203 (2.15) or equivalent, or as defined by the instructor/s

Dependent Courses. E004-2 (3.9)

Attributions. CBC; C, T, L, S

Rationale, Outlook, Purpose, Objectives, and Goals.

- To make students aware of the problem domain of operations research (OR).
- To introduce various models and simulation methods in OR.
- Introducing software tools used in OR practices.
- To make students aware of how the methods are used to solve real life problems.

Syllabus.

1. Linear Programming. Simplex algorithm and simplex method, artificial variable methods. Degeneracy, duality in linear programming, duality theorems, dual simplex method with justification. Integer linear programming problem: pure and mixed integer programming problem, Gomory's all integer programming method. Fractional cut method, all integer and mixed integer linear programming problem, branch-and-bound method.
2. Transportation and assignment problems. Balance and degeneracy in transportation and trans-shipment problems. Duality theory of testing optimality of solution in transportation and trans-shipment problems. Hungarian method of assignment. Maximization, prohibition and other variations of assignment problems.
3. Linear programming. Dynamic programming, sensitivity.

   Nonlinear programming. Kuhn-Tucker conditions. Quadratic programming. Wolfes and Beales algorithm for solving quadratic programming problems.
4. Networking models. Network flows. Maximal flow in the network. Transportation, trans-shipment, and assignment problems as networking problems. Network scheduling by PERT/CPM technique. Resource analysis in network scheduling.
5. Introduction to Software Tools. `Lingo` and `AMPL`.

Suggested Texts/References.

1. Kambo, N. S., *Mathematical Programming Techniques*. Affiliated East-West Press, 2002.
2. Taha, H. A., *Operations research*. Pearson, 2014 (9ed).
3. Sierksma, *Linear and Integer Programming*. CRC Press, 2002.
4. Kantiswaroop, P. K., Gupta, M. M., *Operation Research: An Introduction to Management Science*. S. Chand & Co., 2014.
5. Sharma, J. K., *Operations Research Theory and Applications*. Macmillan Publisher India, 2013 (5ed).
6. N. S. Kambo, *Mathematical Programming Techniques*. Affiliated East-West Press, 2002.

Notes on Pedagogy. Each unit in the syllabus above can be covered in approximately 12 laboratory and 3 "theory" sessions.

Contributor/s. Padma Pingle

3.9 E004-2 Operations Research 2

Credits. 5

Prerequisites. E004-1 (3.8) or equivalent, or as defined by the instructor/s

Dependent Courses. None

Attributions. CBC; C, T, L, S

Rationale, Outlook, Purpose, Objectives, and Goals.

- To make students aware of the advanced techniques in Operations Research (OR).
- Introducing various models & theories used in OR.
- To make students able to apply their knowledge for solving real life problems in OR.

Syllabus.

1. Linear Programming Problem. Advanced techniques: Revised Simplex Method, Simplex Method versus Revised Simplex Method, Bounded variable technique, Parametric Linear Programming, Linear Fractional Programming and their applications, Karmarkar algorithm.

   Sequential problems. Basic terms used in sequencing, n-jobs two machines sequencing problems, processing two jobs through K machines sequencing problems.
2. Queuing Theory. Markovian and Non-Markovian queuing models (i.e., $(M/M/1)$, $(M/M/s)$, $(M/E_k/1)$, $(M, G, 1)$, steady-state probabilities and their characteristics, cost profit models of $(M/M/1)$ queuing systems. Simulation, event type simulation, simulation of a queuing system.
3. Inventory Models. Types of inventories. Reasons for carrying inventories, Inventory control, Inventory carrying costs and factors. Concept of economic order quantity (EOQ) or lot size problems. Deterministic inventory problems with and without shortages, EOQ problems with price breaks. Multi-items deterministic problems. Selective inventory control techniques. Inventory problems with uncertain demand, systems of inventory control (Q-system and P-system).
4. Game Theory. Two-person Zero-sum games, Maximin-Minimax principle. Games without saddle point. Graphical solution of $2 \times n$ and $m \times 2$ games, Dominance property, Arithmetic methods for $n \times n$ games, General solution of $m \times n$ Rectangular games, Limitations and Extensions.

Suggested Texts/References.

1. Kambo, N. S., *Mathematical Programming Techniques.* Affiliated East-West Press, 2002.
2. Taha, H. A., *Operations research.* Pearson, 2014 (9ed).
3. Sierksma, *Linear and Integer Programming.* CRC Press, 2002.
4. Kantiswaroop, P. K., Gupta, M. M., *Operation Research: An Introduction to Management Science.* S. Chand & Co., 2014.
5. Sharma, J. K., *Operations Research Theory and Applications.* Macmillan Publisher India, 2013 (5ed).

Notes on Pedagogy. Each unit in the syllabus above can be covered in approximately 12 laboratory and 3 "theory" sessions.

Contributor/s. Padma Pingle

3.10 E005 Concurrent Computing

Credits. 5

Prerequisites. C109 (2.10), C110 (2.11) or equivalent, or as defined by the instructor/s

Dependent Courses. None

Attributions. CBC; C, T, L, S

Rationale, Outlook, Purpose, Objectives, and Goals. Concurrency is ubiquitous, and not only a part of OS courses. It can also be a program modularization technique whereby applications can be organized as a set of interacting concurrent components. The word "concurrency" not only alludes to "occurring at the same time", but also has other connotations like "agreeing on some thing", or "coming together for a task" etc. While concurrency in the first sense is often conflated with parallel computing, concurrency is broader and more pervasive. This course aims to bring out the basic issues and techniques needed to deal with concurrency.

- Understanding of concurrency in parallel and distributed computing
- Designing and modularising programs using concurrent tasks
- Synchronizing and communicating between tasks in a concurrent program
- (Optional): Formal modeling of concurrent systems

Syllabus.

1. Introduction. Introducing concurrency with simple problems like Readers-Writers, Producer-Consumer, Bounded Buffer, etc., as illustrations. Challenges in concurrency: synchronization, mutual exclusion, deadlock, livelock, starvation, non-determinism. Distinction between concurrent and distributed systems. Relation between timing and concurrency. Concurrency in algorithms and physical concurrency. Example of concurrent systems: operating systems, database systems, web servers.
2. Types of concurrency. (a) Program level – Introduction to the variety of control flows: sequential, coroutines etc. Program execution approaches: single tasking, multitasking, multiprocessing, multicomputing and distributed. (b) Data level – data structures and their concurrency, parallel computing.
3. Inter-process communication. Communication between components in a concurrent program: shared memory, message passing. Communication/Data exchange/Interaction between processes on: time shared systems, client-server systems, distributed systems. Components of a concurrent program versus interaction between processes; similarities and differences.

   Techniques of handling concurrency. Locking, Time stamp ordering, Semaphores, Monitors. Goals: Correctness or fault tolerance.
4. Distributed systems. timing and clock synchronization, time stamps, Chandy-Lamport time ordering. Global snapshot on distributed systems. Examples: from distributed snapshots, Synchronous and asynchronous systems.
5. (Sample: See note 1). Introduction to Android as a programming platform. The basic "HelloWorld" application on Android. Implement algorithms on Android – three sort algorithms as independent programs. IPC on Android – A pair of sort algorithms on shared data set (Scenarios: e.g., (a) One works in place, and the other on a copy – both run concurrently, (b) Both work in place and concurrently, etc. Choose a scenario).

6. (Optional: See note 2). Abstract representation of concurrent (esp. distributed) systems: Introduction to a Process Algebra, e.g., CCS. The Calculus of Communicating Systems: Syntax of the CCS, Operational semantics of the CCS (non-determinism etc.). Worked examples for the CCS.

Suggested Texts/References.

1. Clay Breshears, *The Art of Concurrency: A Thread Monkey's Guide to Writing Parallel Applications*. O'Reilly, 2009.
2. Robin Milner, *Communicating and Mobile Systems: The π Calculus*. Cambridge University Press, 1999.
3. Michel Raynal, *Concurrent Programming: Algorithms, Principles, and Foundations*. Springer, 2013.
4. A. Roscoe, *Theory and Practice of Concurrency*. Prentice Hall, 1997.
5. G. Blake Meike, *Programming Android*. Shroff, 2012.
6. Reto Meier, *Professional Android 4 Application Development (Wrox)*. Wiley, 2012.

Notes on Pedagogy.

1. This course requires programming exercises. The proposal illustrates using Android. However, any suitable system could be used based on the familiarity of the students and the instructor. For example, a Unix/Linux based system would bring out shared memory (`shm*`) system calls, message passing (`msg*`) system calls, and possibly simple socket based IPC programming. Yet another possibility is to use MPI based programming assignments with similar detailing. This component is therefore labeled as "Sample" to suggest that the *means* used to bring out concurrency may be decided by the instructor depending on the circumstances.
2. The formal aspects are truly optional and at the discretion of the instructor. The main goal of including this treatment should be to illustrate the *mathematical modeling* component of the course. The suggested syllabus uses CCS – Calculus of Communicating Systems – by Robin Milner. However, any other useful system – e.g., Petri Nets, CSP (Communicating Sequential Processes – C.A.R. Hoare) etc. – can be used.

Contributor/s. Abhijat Vichare (`https://www.linkedin.com/pub/abhijat-vichare/2/822/828`)

3.11 E006 High-Performance Computing

Credits. 5

Prerequisites. C109 (2.10), C110 (2.11) or equivalent, or as defined by the instructor/s

Dependent Courses. None

Attributions. CBC; C, T, L, S

Rationale, Outlook, Purpose, Objectives, and Goals.

Syllabus.

1. HPC programming platforms. Implicit Parallelism: trends in microprocessor architectures, memory system performance limitations, control structure of HPC platforms, communication model, physical organization, architecture of parallel computer, interconnection networks, network topologies, static, dynamic interconnection networks, cache coherence in multiprocessor systems, communication costs, message passing costs
2. Programming using message-passing. Principles of message passing programming, send and receive operations, blocking and non-blocking message passing, Message passing interface, introduction to MPI routines, data types, concept of communicators, communication domain, communicator groups, creating topologies using MPI, overlapping communication with computation, MPI syntax for frequently used communication calls related to send, receive, barrier, broadcast, reduction, prefix, gather, scatter, all-to-all communication. programs with MPI for addition/multiplication of list of random numbers, matrix-matrix multiplication, bubble sort, shell sort, quick sort, bucket sort, sample sort etc.
3. Parallel algorithm design. Decomposition, tasks, dependency graphs, granularity, concurrency, task interaction, processes and mapping, decomposition techniques: recursive, data, speculative, hybrid, characteristics of tasks and intertask interactions, mapping techniques for load balancing, static mapping, dynamic mapping, methods for containing interaction overheads, parallel algorithm models: data parallel, task-graph, work pool, master-slave, producer-consumer or pipeline model
4. Basic communication operations. Personalized Communication, Collective Communication, Collective communication operation algorithms on ring, mesh, hypercube topologies and their cost analysis, improving speed of communication operations
5. Parallel algorithms for linear algebra. Matrix-vector multiplication with 1-D, 2-D partitioning, matrix-matrix multiplication: simple algorithm (1-D partitioning), Cannon's algorithm (2-D partitioning), DNS algorithm (3-D partitioning), solving system of linear equations with simple Gaussian elimination algorithm (1-D partitioning), 1-D partitioning with pipelined communication and computation, 2-D partitioning with pipelined communication and computation, Gaussian elimination with partial pivoting, solving a triangular system with back substitution, parallel algorithm for Jacobi's iterative method and Gauss-Seidel iterative method for solving system of linear equations.
6. Analytical modeling of parallel programs. Overheads in parallel programs, performance metrics such as execution time, total parallel overhead, speedup, efficiency, cost, effect of granularity on performance, scalability, scaling characteristics, isoefficiency metric of scalability, cost-optimality, isoefficiency function, degree of concurrency and isoefficiency function, minimum execution time, minimum cost-optimal execution time, asymptotic

analysis of parallel programs, other scalability metrics Cost analysis of parallel programs developed in the course work.

Suggested Texts/References.

1. Ananth Grama, Anshul Gupta, George Karypis and Vipin Kumar, *Introduction to Parallel Computing*. Pearson Education, 2004.
2. V. Rajaraman and C. Siva Ram Murthy, *Parallel Computers: Architecture and Programming*. Prentice-Hall India, 2000.
3. Ian Foster, *Designing and Building Parallel Algorithms*. Addison-Wesley, 1995.
4. V. Rajaraman, *Elements of Parallel Computing*. Prentice Hall, 1990.
5. Barry Wilkinson and Michael Allen, *Parallel Programming: Techniques and Applications Using Networked Workstations and Parallel Computers*. Pearson India, .
6. Michael T. Heath, *Scientific Computing*. Tata McGraw-Hill, .
7. Michael Quinn, *Parallel Programming in C with MPI and OpenMP*. Tata McGraw-Hill, .

Notes on Pedagogy.

Contributor/s. Vaishali Shah (https://www.researchgate.net/profile/Vaishali_Shah10)

3.12 E007 Advanced Data Analysis

Credits. 2

Prerequisites. C206 (2.18) or equivalent, or as defined by the instructor/s

Dependent Courses. None

Attributions. CBC; C, T, L, S

Rationale, Outlook, Purpose, Objectives, and Goals. Given the basic background in statistical modeling developed in prior courses, this course intends to expose the student to data analysis in a hands-on and problem-centric manner, so as to develop a feel for the challenges involved. At the end of this course, the student is expected to develop understanding about

1. formulating the problem in the light of the (scientific) question being explored;
2. choosing a statistical method that is most appropriate for the problem;
3. adapting or developing computational tools; and
4. evaluating results of the analysis and the statistical models involved critically.

This course is inspired by similarly-spirited courses such as http://www.stat.cmu.edu/~cshalizi/uADA/12/ and http://stat.ethz.ch/education/semesters/ss2010/CompStat.

Syllabus. An assortment of data analysis problems from any selection of fields at the discretion of the instructor/s. Problems should be chosen to reflect the diversity of (scientific) questions probed as well as that of statistical models and methods, such as (but not limited to): simple and multiple linear regression; model selection; finite mixture models; nonparametric methods for regression, density estimation, and classification (kernel methods, smoothing splines, classification and regression trees, additive models, etc.); resampling, bootstrap, and cross-validation methods.

Suggested Texts/References.

1. Cosma Rohilla Shalizi, *Advanced Data Analysis from an Elementary Point of View*. Unpublished, 2014. Available as http://www.stat.cmu.edu/~cshalizi/uADA/12/lectures/ADAfaEPoV.pdf.
2. Peter Bühlmann and Martin Mächler, *Computational Statistics*. Unpublished, 2008. Available as https://stat.ethz.ch/education/semesters/ss2010/CompStat.

Notes on Pedagogy. An apt name that conveys the spirit of this course better could have been *Delving into Data Dungeons*. This is intended to be a highly hands-on, interactive course involving an appropriate number of individual and group projects by the students. Apart from the projects, additional case studies may be presented by the instructor or guest speakers so as to develop perspective on the challenges involved in real-life data analysis situations.

Contributor/s. Mihir Arjunwadkar (http://cms.unipune.ac.in/~mihir)

3.13 E008 Computing with Java

Credits. 2

Prerequisites. C110 (2.11) or equivalent, or as defined by the instructor/s

Dependent Courses. None

Attributions. CBC; L, S

Rationale, Outlook, Purpose, Objectives, and Goals. Upon successful completion of this course, the student will

1. Understand basics of object-oriented programming (OOP), syntax, semantics of Java.
2. Design an algorithm to solve problems of various kinds in modeling and simulation and implement using Java programming language.
3. Debug the code to spot logical errors, exceptions etc.
4. Write reasonably complex Java code/applets for various problems in modeling and simulation.

Syllabus.

1. Overview of Java Programming. Compiling and Running a Java program. Coding Standards. Introduction to Java programming language. Data types, operators and control structures. Primitive data classes.
2. OOAD. Class, object, inheritance, Class Design and Implementation, class responsibilities, data encapsulation, Polymorphism.
3. Exception Handling. Exception handling in Java.
4. Java Generics. generic programming, ready made classes and generic data structures. Generic Algorithms. Enumerations, autoboxing, and annotations. The Collections Framework
5. Threads. Thread handling in Java.
6. GUI. AWT library. Window, Controls, events, callback, event handlers, frames, graphics, image handling.
7. Applets. Application development and animations.

Suggested Texts/References.

- Herb Schildt, *Java: The Complete Reference*. McGraw Hill Education (India) Private Limited, 2013.
- Various web resources; especially, http://docs.oracle.com/javase/7/docs/api/.

Notes on Pedagogy.

Contributor/s. Bhalchandra Gore (http://cms.unipune.ac.in/~bwgore)

3.14 E009 Theory of Computation

Credits. 5

Prerequisites. As defined by the instructor/s

Dependent Courses. None

Attributions. CBC; C, T, L, S

Rationale, Outlook, Purpose, Objectives, and Goals. This is an introduction to the formal theory of computation and its modeling applications.

Syllabus.

1. Introduction to Languages. Symbols, strings, words and languages. Symbolic dynamics, dynamics as language. Examples of languages. Finite representation of languages. String induction principles.
2. Finite Automata. Functions as tables: introduction to theory of automata. Regular expressions and languages. Equivalence and simplification of regular expressions. Finite automata and labeled paths. Isomorphism of finite automata. Algorithms for checking acceptance and finding accepting paths. Simplification of finite automata. Proving the correctness of finite automata. Empty-string finite automata. Nondeterministic finite automata. Deterministic finite automata. Closure properties of regular languages. Transfer matrices and finite automata. Solving real-life problems with finite automata.
3. Context-Free Grammars. Examples of languages which are not regular. State minimization. The pumping lemma for regular languages. Context-free grammars, parse trees, stacks and queues. Dynamical systems generating context-free languages. Functions with "internal memory" and push-down automata. Isomorphism of grammars. Derivations, Converting between parse trees and derivations. Simplification and ambiguity of grammars. Determinism and parsing. Pumping lemma for context free grammars. Chomsky normal form. A parsing algorithm.
4. Turing Machines. Examples which are not context free. Chomsky hierarchy. Another look at symbolic dynamics and coding theory for examples of dynamical systems in various levels of Chomsky hierarchy. Computing with dynamical systems. Functions with "external memory" and Turing machines. Computing with Turing machines. Extensions of Turing machines. Random access Turing machine. Non-deterministic Turing machines. Chaotic systems as Turing machines.
5. Universal Turing Machines, Complexity, Computability. Universal Turing machines. Church-Turing thesis. Halting problem. Undecidable problems. Tiling problem and the Potts model. Computability and complexity theory. Classes P and NP. Cook's theorem and P-NP completeness theorems.
6. Formal Computation as a Modeling Paradigm. A judicious selection of topics such as: symbolic dynamics of dynamical systems, biological sequences and stochastic grammars, computational musicology, computational linguistics, natural language processing, L-systems, automata in game theory, etc.

Suggested Texts/References.

1. H. Lewis and C. Papadimitrion, *Elements of Theory of Computation.* Prentice-Hall, 1998.
2. V. E. Krishnamurthy, *Introductory Theory of Computer Science.* Springer-Verlag, 1985.

Notes on Pedagogy. Formal development should be coupled with adequate emphasis on modeling applications, and preferably some hands-on work in any form such class projects, etc.

Contributor/s. Ashutosh Ashutosh (https://www.linkedin.com/profile/view?id=198572337), Abhijat Vichare (https://www.linkedin.com/pub/abhijat-vichare/2/822/828)

3.15 E010 Functional Programming

Credits. 2

Prerequisites. As defined by the instructor/s

Dependent Courses. None

Attributions. CBC; L, S

Rationale, Outlook, Purpose, Objectives, and Goals. Upon successful completion of this course, the student will be able to

1. Understand basics of functional programming.
2. Design an algorithm to solve problems of various kinds in modeling and simulation and implement using functional language.
3. Debug the code to spot logical errors, exceptions etc.
4. Write reasonably complex code for solving various problems in modeling and simulation.

Syllabus.

1. Introduction to theoretical framework for describing functions and their evaluation, variable binding and substitution, effective computability, Turing machine and Lambda calculus.
2. Dynamically and Statically Typed Functional Languages.
3. Other domain specific programming languages based on/implementing functional programming concepts; e.g, `R`, `SQL`, etc.
4. How does the chosen programming language (LISP/Haskell) implement the above concepts?
5. First-class and higher-order functions, pure functions, recursion.
6. Comparison with other programming paradigms.
7. Declarative *vs.* imperative, using pipelines, Computation by expression evaluation.
8. Reliability.
9. Syntax, coding style and other aspects of programming in the chosen functional language.

Suggested Texts/References. As recommended by the course instructor.

Notes on Pedagogy. Any functional programming language like such as `LISP`, `Scheme`, or `Haskell` can be chosen for this course. The concepts of functional programming, how they are used in the chosen language and programming in that language for M&S problem-solving should be clearly brought out by the instructor.

Contributor/s. Bhalchandra Gore (`http://cms.unipune.ac.in/~bwgore`),
Charulata Patil (`charulata@cms.unipune.ac.in`)

3.16 E011 M&S with `Python`

Credits. 2

Prerequisites. C110 (2.11) or equivalent, or as defined by the instructor/s

Dependent Courses. None

Attributions. CBC; L, S

Rationale, Outlook, Purpose, Objectives, and Goals. `Python` offers a powerful means for M&S via its intuitive object-oriented framework and in-built libraries. The goal of this course is not the introduction to `Python` but demonstration of how `Python` can be used in mathematical modeling. At the end of the course students are expected to develop `Python` programs to implement intermediate level of mathematical models.

Syllabus.

1. Introduction. 'Hello world' program, Understanding `Python` shell and environment. Running the codes.
2. Data and Control Structures. Data types and objects. Introduction to conditionals (`if`) and loops (`for` and `while`). Loading packages.
3. Functions. Defining and using functions. Using built-in functions. Recursion.
4. Advanced Mathematics. Examples of using `numpy, scipy`. Simple 2D and 3D plotting.
5. User Input. Reading and writing the data from/to terminal and files. Formatting output. Converting data types. `try-except` construct.
6. Strings and Lists. Operations on stings. List, list-comprehensions, list of lists.
7. Classes. User defined classes, objects, methods, and functions.

Suggested Texts/References.

1. David Beazley, Brian K. Jones, *Python Cookbook*. O'Reilly Media, 2013.
2. Mark Lutz, *Programming Python*. O'Reilly Media, 2010.
3. The Official Python Documentation (`https://docs.python.org/`).

Notes on Pedagogy. Since the focus of the course is using `Python` for modeling, the syntax could be introduced as a necessity to solve the given problem. Ideally the aim of the course could be to have one `Python` project at the the end of the term, and necessary syntax and other tools are taught as the requirement along the development.

Contributor/s. Bhalchandra Pujari (`http://cms.unipune.ac.in/~bspujari`)

4 Professional Development Programme (PDP)

4.1 Structure of the PDP Curriculum

Semester 1/3

Credits: 0; attendance and participation a must, no evaluation/grading

Code (Section)	Course Name	Credits
P001-1 (4.2)	Introduction to `Linux` 1	0
P002-1 (4.4)	Technical Communication 1	0
P003-1 (4.6)	Life Skills 1	0

Semester 2/4

Credits: 0; attendance and participation a must, no evaluation/grading

Code (Section)	Course Name	Credits
P001-2 (4.3)	Introduction to `Linux` 2	0
P002-2 (4.5)	Technical Communication 2	0
P003-2 (4.7)	Life Skills 2	0

4.2 P001-1 Introduction to Linux 1

Credits. 0

Prerequisites. None

Dependent Courses. P001-2 (4.3)

Attributions. PDP; W

Rationale, Outlook, Purpose, Objectives, and Goals. This course is intended for the beginner to get started with the GNU/Linux operating system for day-to-day tasks. Specifically, the course avoids both the "computer science" approach as well as the "computer operator"-oriented technical labour. The broad focus of the course is defined by the following:

1. What is Linux, and why Linux?
2. Introduction to Linux and the open-source philosophy.
3. Working knowledge of Linux.
4. Knowledge of Linux tools, commands (and hacks) for editing, compiling, debugging, etc.
5. An overview of how computers/networks and peripheral devices work.
6. Understanding system security, backup, integrity.

Syllabus.

1. Introduction to Linux. History, philosophy, common concepts. GNU and Linux. Different flavors of Linux: Debian/Ubuntu, Fedora/CentOS, etc.
2. Bare-Basics Installation. Obtaining/downloading a Linux distribution; MD5 check. Creating a live CD or USB pen drive. Typical installation.
3. The Vanilla User. Initial system boot. Login screen. Exploring the desktop. Common applications: internet, office, multimedia, graphics, accessories, system tools, etc. Finding help on the internet.
4. Command-Line Basics. Invoking commands in the shell terminal. Forward and backward search. Command and filename completion. Commands such as `login`, `logout`, `shutdown`, `reboot`, etc. Finding help via `man` and `info`.
5. Plain-Text Editing. `gedit`, `vim`.
6. The Linux Filesystem. `/`, `$HOME`, and the file system hierarchy. Managing files and folders. Searching files through `find` and `locate`. File types and ownership. Basic file system commands such as `ls`, `rm`, `mv`, `cp`, `pwd`, `mkdir`, `rmdir`, `cd`, `chmod`, etc.
7. Bare-Basic System Tasks. The all-powerful `root` user, `sudo`, safety/security considerations. Software maintenance using `yum/apt`. Adding and deleting users, and ownership of files. File size management and backup using `gzip/bzip2`, `gunzip/bunzip2`, `tar`. Useful commands such as `date`, `df`, `du`, etc.
8. Text and Document Processing. A functional introduction to LaTeX and friends. (Optional) LaTeX and Unicode Indic scripts.

Suggested Texts/References.

1. Richard Petersen, *Linux: The Complete Reference*. McGraw-Hill Education, 2007.
2. http://www.linux.org/, http://www.tldp.org/, etc.

Notes on Pedagogy. The course is best run in an interactive, hands-on, workshop mode; active student participation is critical.

Contributor/s. Bhalchandra Gore (http://cms.unipune.ac.in/~bwgore)

4.3 P001-2 Introduction to Linux 2

Credits. 0

Prerequisites. P001-1 (4.2) or equivalent, or as defined by the instructor/s

Dependent Courses. None

Attributions. PDP; W

Rationale, Outlook, Purpose, Objectives, and Goals. This course builds on the material covered by the prerequisite course P001-1 (4.2), and covers a few advanced Linux topics of practical everyday utility.

Syllabus.

1. Text Processing. `regexp`, `awk`, `sed`, `grep`, `split`, `paste`, etc.
2. Understanding Linux Filters. `grep`, `awk`, `sed` as filters. Other common filters: `sort`, `head`, `tail`, `tr`, `cut`, `od`, `paste`, `split`, `uniq`, `more/less`, `tee`, `lp`, etc.
3. Understanding Linux Processes. Viewing processes using `ps` and `top`. Process attributes. Parent-child relations. Background and foreground processes. Process priorities. Scheduling processes in the future using `time` and `at`. Detaching processes from the console.
4. Shell and shell scripting. Shell fundamentals. Shell variables and environment. `PATH` and other variables. Command line, command history, command line shortcuts, command substitution. Filename expansion characters. Standard input, output, and error devices. Pipes, aliases, quoting, control sequences, other special characters. Other shell features.

   `bash` shell scripting. Constructs, decision making, redirection, loops, variables, command substitutions, etc.
5. Linux Networking and Tools. Networking Basics: TCP/IP, IP address, private/home networks, LAN, WAN, connecting two computers (wired/wireless), network switches, routers, client-server architectures, etc. Connecting to networks (LAN, Dial-Up, WiFi), static and dynamic IP, `netconfig`, `ipconfig`, network configuration files. `ping`, `ftp`, `ssh`, `scp`, `traceroute`, etc. DNS tools.

Suggested Texts/References.

1. Richard Petersen, *Linux: The Complete Reference*. McGraw-Hill Education, 2007.
2. Robert Mecklenburg, *Managing Projects with GNU Make(Nutshell Handbooks)*. O'Reilly Media, 2004.
3. Richard Blum, *Linux Command Line And Shell Scripting Bible*. Wiley India, 2011.
4. http://www.linux.org/, http://www.tldp.org/, etc.

Notes on Pedagogy. The course is best run in an interactive, hands-on, workshop mode; active student participation is critical.

Contributor/s. Bhalchandra Gore (http://cms.unipune.ac.in/~bwgore)

4.4 P002-1 Technical Communication 1

Credits. 0

Prerequisites. None

Dependent Courses. P002-2 (4.5)

Attributions. PDP; W

Rationale, Outlook, Purpose, Objectives, and Goals. There is no fixed syllabus for this course. However, the focus of this course broadly includes: Basic-to-intermediate-level proficiency in English; grammar and punctuation; conveying what is intended through good, meaningful, understandable sentences; using dictionary, thesaurus, and such other language resources and tools; reading and understanding technical documents; etc.

Syllabus.

Suggested Texts/References.

1. Joseph E. Harmon and Alan G. Gross, *The Craft of Scientific Communication.* The University of Chicago Press, 2010.
2. Virginia Tufte, *Artful Sentences: Syntax as Style.* Graphics Press, 2006.
3. Lynne Truss, *Eats, Shoots & Leaves: The Zero Tolerance Approach to Punctuation.* Profile Books, 2003.

Notes on Pedagogy. The course is best run in an interactive, hands-on mode. Active student participation is critical.

Contributor/s. Mihir Arjunwadkar (`http://cms.unipune.ac.in/~mihir`)

4.5 P002-2 Technical Communication 2

Credits. 0

Prerequisites. P002-1 (4.4) or equivalent, or as defined by the instructor/s

Dependent Courses. None

Attributions. PDP; W

Rationale, Outlook, Purpose, Objectives, and Goals. There is no fixed syllabus for this course. However, the focus of this course broadly includes: the art of listening (in general, and in the technical context in particular); the art of ensuring that content gets conveyed to the audience exactly as intended; technical writing skills; technical presentation skills; etc.

Syllabus.

Suggested Texts/References.

1. Gerald J. Alred, Charles T. Brusaw and Walter E. Oliu, *Handbook of Technical Writing.* Bedford/St. Martin's, 2012.
2. Phillip A. Laplante, *Technical Writing: A Practical Guide for Engineers and Scientists.* CRC Press, 2012.
3. Kenneth G. Budinski, *Engineer's Guide to Technical Writing.* ASM International, 2001.
4. Shelton, James H., *Handbook for Technical Writing.* NTC Contemporary, 1994.
5. Joseph E. Harmon and Alan G. Gross, *The Craft of Scientific Communication.* The University of Chicago Press, 2010.
6. Michael Alley, *The Craft of Scientific Writing.* Springer, 1996.

Notes on Pedagogy. The course is best run in an interactive, hands-on mode; active student participation is critical.

Contributor/s. Mihir Arjunwadkar (`http://cms.unipune.ac.in/~mihir`)

4.6 P003-1 Life Skills 1

Credits. 0

Prerequisites. None

Dependent Courses. P003-2 (4.7)

Attributions. PDP; W

Rationale, Outlook, Purpose, Objectives, and Goals. There is no fixed syllabus for this course. However, the focus of this course broadly includes: Reading-comprehension and self-study skills; working in a group; using the internet wisely; plagiarism, and how to avoid it; surviving computers through ergonomics, posture, and work habits; etc.

Syllabus.

Suggested Texts/References.

Notes on Pedagogy. The course is best run in an interactive, hands-on mode, with qualified experts (such as psychologists) as teachers. active student participation is critical.

Contributor/s. Mihir Arjunwadkar (`http://cms.unipune.ac.in/~mihir`)

4.7 P003-2 Life Skills 2

Credits. 0

Prerequisites. P003-1 (4.6) or equivalent, or as defined by the instructor/s

Dependent Courses. None

Attributions. PDP; W

Rationale, Outlook, Purpose, Objectives, and Goals. There is no fixed syllabus for this course. However, the focus of this course broadly includes: Thinking skills and styles; time and stress management; M&S career paths; employment: designing resume/CV, professional networking, job search, facing interviews; etc.

Syllabus.

Suggested Texts/References.

Notes on Pedagogy. The course is best run in an interactive, hands-on mode, with qualified experts (such as psychologists) as teachers. Active student participation is critical.

Contributor/s. Mihir Arjunwadkar (`http://cms.unipune.ac.in/~mihir`)