Advanced Diploma Programme in Modeling and Simulation

May 2, 2005
Minor Update May 2, 2005

\LaTeX-ed May 2, 2007
About This Document

This document outlines an academic programme, the Advanced Diploma Programme in Modeling and Simulation, designed by the people at the Centre for Modeling and Simulation, University of Pune, and approved by the University of Pune.

Citing This Document

Complete citation for this public document is as follows:


About the Centre

The Centre for Modeling and Simulation, University of Pune, was established in August 2003 to promote, support and facilitate academic and research activities that use modeling, simulation and computation as the “third scientific methodology” (besides theory and experiment) and transcend the traditional boundaries separating established scientific disciplines. At the time of writing this document, the Centre possesses three full-time faculty, one postdoctoral fellow, a small support staff, plus considerable computational expertise and resources. For more information about the Centre, please visit our website http://cms.unipune.ernet.in/.

Acknowledgments

Many people have contributed to the creation of this document and this programme. Their time and effort, contributions and insights, and comments and suggestions have all gone a long way towards bringing this document to its present form. The Centre values, appreciates and acknowledges all these forces that shaped this document and this programme, and would like to extend profound and sincere thanks to all of them. A comprehensive list of all those who contributed, along with a brief history of this document, can be found in Appendix A.
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1 M&S Programme Summary

Title of the Programme
Advanced Diploma Programme in Modeling and Simulation (the M&S Programme for short).

Duration of the Programme
12 months (48 weeks) split into 3 trimesters of 16 weeks each.

Nature of Programme
Full time\(^1\).

Programme Status
The M&S programme will be run as an **autonomous** programme by the Centre for Modeling and Simulation, University of Pune.

Eligibility
1. B.E. or equivalent in any branch of engineering OR Master’s degree in any science, arts, or commerce discipline, AND
2. background in mathematics equivalent to the University of Pune F.Y.B.Sc. mathematics syllabus,

Selection Criteria
1. academic record, AND
2. performance in a qualifying examination.

Number of Seats
Not more than 30, and possibly smaller for a particular academic year.

Total Number of Credits
48.

Credit Breakup
8 core courses (28 credits) + 1 elective course (4 credits) + project (12 credits) + term papers (4 credits).

Fees
Per student fees for the entire M&S programme: Rs. 20347 for students from the state of Maharashtra, Rs. 29147 for students from outside of Maharashtra, subject to University of Pune norms and policies as applicable.

\(^1\)In future, the M&S programme may also be run in a part-time mode (7.5 contact hours per week+minimum programme duration of 24 months). The Centre does not plan to run the M&S programme in the part-time mode during academic year 2005-06 or in the near future.
2 The M&S Programme at a Glance

• The advanced diploma programme in modeling and simulation, also called the M&S Programme, designed by the Centre for Modeling and Simulation, University of Pune, is a fast-paced and vigorous academic training programme that consists of core courses, an elective or specialization, term papers, and a project. The M&S Programme uses a credit system that is manifestly compliant with the existing University of Pune credit system. One credit is thus equivalent to one clock hour of contact (between faculty and students) per week for 15 consecutive weeks, and a course could be of 1, 2, 3 or 4 credits.

• This is a full-time programme. The duration of the M&S Programme is exactly 12 months, broken up into three trimesters of 16 weeks each. The programme year should ideally and preferably start on July 1 of one academic year and end on June 30 of the next.

• The first two trimesters are devoted to coursework that consists of a total of 8 foundation (or core) courses totaling to 28 credits, plus one elective course (or specialization) of 4 credits. Each trimester is broken up into fourteen weeks of instruction, one week for exam preparations and one week for actual end-trimester examinations. Evaluation is based on (a) continuous assessment throughout the trimester, including assignments and class participation (b) final examination.

• The third trimester is devoted entirely to project work. Evaluation of the project is based on periodic monitoring of progress, a project report and a presentation cum open defense. Grade for the project component (satisfactory or otherwise) is to be mentioned separately from the grades for the rest of the programme. Students are to be encouraged to decide on and start preparing for their projects as early on in the programme as possible. The project is considered equivalent to 12 credits.

• In addition, in order to foster (a) self-study skills, resourcefulness, and independence, (b) the ability to read technical and research literature, and (c) presentation skills, a student is expected to present two term papers on topics of his or her interest and related to modeling and simulation, any time during the programme year. Evaluation of this component is to be based on (a) the term paper/report itself, and (b) the presentation. This component is considered equivalent to 4 credits.

• The credit total of the entire programme thus comes to 48 credits = 28 (foundations) + 4 (elective) + 12 (project) + 4 (term papers).
3 Introduction

This document outlines a multidisciplinary academic programme, the Advanced Diploma Programme in Modeling and Simulation, designed by the Centre for Modeling and Simulation, University of Pune. For the purpose this document, this programme may be referred to as the M&S Programme or, simply, as the programme. The Centre for Modeling and Simulation, University of Pune, may similarly be referred to as the Centre. In this section, we present our perspective on the modeling and simulation enterprise which forms the basis for the proposed structure of the M&S Programme.

3.1 The Modeling and Simulation Enterprise

Model, n. 1 a usually miniature representation of something; also : a pattern of something to be made 2 an example for imitation or emulation 3 archetype 4 a description or analogy used to help visualize something (as an atom) that cannot be directly observed 5 a system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs.

source: www.merriam-webster.com

Simulation, n. 1 The imitative representation of the functioning of one system or process by means of the functioning of another <a computer simulation of an industrial process> 2 Examination of a problem often not subject to direct experimentation by means of a simulating device.

source: www.merriam-webster.com

Simulation, n. 1 Imitation or representation, as of a potential situation or in experimental testing 2 Representation of the operation or features of one process or system through the use of another: computer simulation of an in-flight emergency 3 Attempting to predict aspects of the behaviour of some system by creating an approximate (mathematical) model of it. This can be done by physical modeling, by writing a special-purpose computer program or using a more general simulation package, probably still aimed at a particular kind of simulation (e.g., structural engineering, fluid flow). Typical examples are aircraft flight simulators or electronic circuit simulators. A great many simulation languages exist; e.g., Simula.

source: www.dictionary.com

A model tries to capture the essential features of a system under scrutiny. A simulation, on the other hand, attempts to represent a model of the system under study using some other well-understood system, the simulation system, wherein features of interest of the system under study are represented using properties of the simulation system. The correctness of representation of features of interest embodied by the model, and whether one system could at all be simulated by another should be the principal concerns of a “theory” of simulation. Assuming that the model did capture essential ingredients of the system being studied, and that the simulation
system is capable of representing the model to sufficient accuracy, the corresponding simulation could be expected to mimic the behaviour of the underlying real-life system.

Most often, mathematics is used to model the system under study. Indeed, all scientific theories can be thought of as models representing aspects of “reality” to within their own respective domains of applicability. The most challenging modeling and simulation problems arise when the system under study is neither well-understood nor, possibly, mathematised. For example, in comparison with physical systems, complex phenomena such as human social behaviour are neither as well-understood, nor are as mathematised, in microscopic detail, as physical theories. Construction of a simulation system for such phenomena may have somewhat nebulous boundaries between an art and a science. Further, validity bounds of the mathematical theory used in constructing the underlying mathematical model for a system has a direct influence on the reliability of the simulation system. The degree of identity (or similarity) between the behaviour of the real system and the simulated system needs to be determined so as to enable making of valid inferences based on observations of the simulated system.

A mathematical model typically extracts essential features of the system under study from the knowledge domain. For example, the mathematical model of air flight would have to incorporate fluid dynamical statements about the properties of air as a fluid system. A typical modern scientific team working on a challenging real-life problem consists of domain experts (e.g., experts in fluid dynamics), mathematical modeling experts, and experts from the field that is being used to construct the simulation system. In case modern digital computers are used to perform a simulation, the field of expertise for constructing a simulation system would be computer science and engineering. Other cases, for example, a full-scale flight simulation system, could involve expertise from almost every branch of engineering and robotics just to construct the simulation system.

A simulation is thus built using these three principal components; namely, (a) domain expertise, (b) mathematical modeling strategies, and (c) simulation system methodologies (including technology).

In modern times, digital computers have emerged as the preferred simulation system to perform simulations on. Usually, a mathematical model of the system under scrutiny is programmed into a computer and then run, and the behaviour of the model as observed in this simulation is used to make inferences about the real system that is being modeled and simulated. It appears that the use of computers saves costs because employing them in place of full-scale physical simulation systems reduces the engineering overheads (although the scientific principles at the base still need to be incorporated).

If we choose to use a computer to perform simulations, then its behaviour and properties as a simulation system must be “well-understood”: this implies that an academic programme designed around the use of computers as simulation systems of choice must have sufficient theoretical and practical content to ensure strong foundations in computation.
3.2 Need for a Programme in Modeling and Simulation

The rapid pace of advances in computer and computation-related technologies over last few decades and the ever-increasing availability of comparatively inexpensive raw computing power have encouraged the use of computation in general, and simulation methods in particular, wherever quantitative reasoning has a significant role to play. This includes all branches of the scientific and technological endeavour.

Typical degree programmes (such as a two-year Masters programme in physical sciences mathematics and statistics, or Bachelors/Masters programmes in an engineering discipline) often include an introductory course on programming, and perhaps another one on domain-specific computational methods. Nevertheless, a sound foundation in all three aspects of modeling and simulation is usually impossible to develop during such courses given the constraints and workload of a typical degree programme.

The M&S Programme designed by the Centre hopes to fill the gap between (a) a conventional degree programme and a research (Ph.D.) programme involving extensive computational and simulative research, and (b) a conventional degree programme and industrial R&D work requiring substantial background in modeling and simulation. From another perspective, the M&S Programme is geared to create a breed of problem solvers with a breadth and perspective on modeling, good training in simulation methods, and the ability to generate reasonable solutions for problems not necessarily encountered previously.

4 Programme Design Considerations

4.1 From an Academic Perspective

As we saw earlier, a simulation is built on

- domain expertise,
- mathematical modeling strategies, and
- simulation system methodologies (including technology).

An advanced diploma programme such as the present one may be designed such that at the successful completion of training, a student may be one of the following:

1. **Conversant** with the basic principles in all the three components, or
2. **Conversant** with basic principles in the mathematical and simulative components, but unaware of any domain expertise, or
3. **Conversant** with only the simulative components, but unaware of domain expertise and mathematical methods, or
4. Be **skilled**, as opposed to **conversant**, with the basic principles of all the three components, but be **aware/conversant** with a few advanced techniques from the three, or
5. Be **skilled**, as opposed to **conversant**, with the basic principles of mathematical and simulational components, but be **aware/conversant** with a few techniques from the first, or

6. Be **skilled**, as opposed to **conversant**, with the basic principles of simulational components, but be **aware/conversant** with a few techniques from the first and the second\(^2\).

All possibilities other than those above are intuitively judged to be more intensive and hence most likely to be out of the time bound of a one-year programme. (1)–(3) have been included because given that the proposed course is a post-graduate diploma course, it may find favour to be licensed to outside entities for a wider spread\(^3\). (4)–(6) are a set of levels of decreasing intensity, but admissible for a University post-graduate diploma course spanning 12 months. The alternative (4) is the most intense one, requiring active involvement of experts in all the three components, thus unsuitable for operation by the Centre in its current state.

Alternative (5) is the most practical alternative for the **M&S Programme**; we have thus proposed a course structure based on this alternative. Nevertheless, we would like to build provisions into the programme structure to offer specialized expert-level courses as and when domain experts become available.

### 4.2 From a Student’s Perspective

A typical candidate looks at a degree or a diploma from the point of view of job prospects and at a diploma as a value addition. Employment opportunities for a graduate of the **M&S Programme** are most likely to come from:

- Research programmes leading to an advanced degree such as Ph.D.
- Research-oriented support positions in research institutions.
- Industries and organizations that require simulation-based methodologies.

### 5 Objectives and Outcomes

Assuming that alternative (5) in Section 4.1 is the way to go, then at the end of the diploma, we expect that a graduate of the **M&S Programme** to be the following:

- A problem solver with a breadth and perspective on modeling, good training in computation and simulation methods, and the ability to generate reasonable solutions for problems not necessarily encountered earlier.

\(^2\)This last alternative is most suitable for an institution like the Department of Computer Science, where the focus is quite different, and simulation is one part of the many aspects that need to be covered. We disregard this alternative for the **M&S Programme**.

\(^3\)Needless to say that the Centre plans **not** to do so before the **M&S Programme** and the Centre itself are well-established.
Outside of his or her knowledge domain, (s)he is able to create a computer representation of a specific detailed description of the problem domain given that a domain expert has distilled the computational essence for him or her.

- Familiar with the current state of relevant technologies, and from familiar to skilled in a variety of relevant software tools and methodologies.

6 The Prospective Student

6.1 Prerequisites

Structure of the M&S Programme is built around the assumption that a prospective student satisfies these three principal prerequisites:

- At least a Bachelor’s degree in an engineering discipline OR a Masters degree in a science, commerce or arts discipline, AND
- A demonstrable background in mathematics at the level of the current University of Pune first-year B.Sc. mathematics syllabus (to be assessed via a qualifying (or entrance) examination (see Section 6.2) and the academic record), AND
- Basic computer usage skills (to be assessed via a qualifying (or entrance) examination (see Section 6.2) preferably with some programming experience.

6.2 Selection

Students will be selected on the basis of

1. academic record,
2. qualifying (or entrance) examination, and
3. statement of purpose.

The qualifying (or entrance) examination will be designed to test basic analytical and reasoning skills, mathematics background, and computer literacy. Passing threshold for the qualifying (or entrance) examination will be at 60% for both (open and reserved) categories. The Centre will select not more than 30 top-scoring candidates consistent with University norms on reservation.
7 Academic Structure

The M&S Programme consists of the following four components. Section 7.1 presents our outlook (in the design) and guidelines (for conducting the M&S programme).

1. Foundation (or Core) Courses (Section 7.2).
2. Elective (Section 7.3).
3. Project (Section 7.4).
4. Term Papers (Section 7.5).

7.1 Outlook and Guidelines

Given the highly multidisciplinary, vigourous and compact nature of the M&S Programme, we find it highly essential to adopt the following outlook in designing the proposed course work (these would serve as the essential guidelines when running the M&S programme):

- Rigour and clarity are not always synonymous: concepts need to be emphasized from a practical and application standpoint in place of tedious derivations and rigorous proofs.
- It is highly essential to impart to the students a perspective on modeling and simulation that will bring together this diverse set of concepts into a unified view, both from conceptual and practical points of view.
- The role of well-chosen and well-motivated students, well-designed instruction material, effective presentation methods, and ready availability of academic and computational resources relevant to the M&S programme cannot be overemphasized.
- See Section 7.6 for guidelines on evaluation and grading.

7.2 The Foundations

Essential basics for a programme on modeling and (computational) simulation should come from applied mathematics (includes probability theory and statistics) on one hand and the theory of computation on the other. The essential methodologies required for a computational simulation are simulation methods and software techniques. This justifies the following five-fold logical structure for the foundations of modeling and simulation:

1. Core Mathematics
2. Theory of Computation
3. Perspectives on Mathematical Modeling
4. Perspectives on Probability Modeling
5. Practical Computing: Technologies and Methodologies

In the rest of this section, we expand this logical structure into a set of 8 foundational courses of the M&S Programme, detailed syllabi of which appear in Appendix B.
7.2.1 Core Mathematics

Rationale and Outlook • This group of modules serves to (a) establish a common denominator for mathematical training keeping in mind the students’ diverse and nonuniform mathematical training, (b) equip the student to read through, and to be able to grasp, elementary mathematical treatments of specialized topics, and (c) cover common mathematics prerequisites of other modules.

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<td>Linear Algebra</td>
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<tr>
<td>Discrete Mathematics</td>
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</tr>
<tr>
<td>Probability Theory and Stochastic Processes</td>
<td>B.1.3</td>
</tr>
</tbody>
</table>

Total Number of Contact Hours 60  
Total Number of Credits 4

7.2.2 Theory of Computation

Rationale and Outlook • This group of modules is designed (a) to expose the student to various aspects of the fundamental question “what is computation?”, (b) to introduce formal aspects of programming and of algorithm design and analysis, and (c) to introduce a formalism that has a potentially wide applicability as a formalism for modeling: Two known examples of such modeling contexts outside of conventional computer science home grounds, where, e.g., theory of formal languages has a high utility are analysis of complex systems (characterization of complexity, symbolic dynamics of dynamical systems), and sequence analysis in bioinformatics.

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<td>Algorithm Design and Analysis</td>
<td>B.2.3</td>
</tr>
</tbody>
</table>

Total Number of Contact Hours 60  
Total Number of Credits 4

7.2.3 Perspectives on Mathematical Modeling I

Rationale and Outlook • The utility of applied mathematics as a formalism for modeling needs no justification. This group of modules is intended to cover areas of
applied mathematics most commonly encountered in modeling and simulation contexts.

In order to emphasize the modeling perspective and maintain focus on applications, we suggest a three-component structure for each of these modules; this structure consists of: (a) basic theory and pertinent mathematical results, (b) perspective on modeling by way of real-life contexts, examples and applications, and (c) relevant numerical methods.

<table>
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<td>Section</td>
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<td>Calculus of Variations</td>
<td>B.3.5</td>
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</table>

Total Number of Contact Hours 60
Total Number of Credits 4

7.2.4 Perspectives on Mathematical Modeling II

Rationale and Outlook • Same as that of Section 7.2.3.

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<td>Numerical Linear Algebra: A User’s Perspective</td>
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</tr>
<tr>
<td>Miscellaneous Topics in Numerical Analysis</td>
<td>B.4.4</td>
</tr>
</tbody>
</table>

Total Number of Contact Hours 60
Total Number of Credits 4

7.2.5 Perspectives on Probability Modeling I

Rationale and Outlook • Probability is the mathematical language for quantifying uncertainty or ignorance, and is the foundation of statistical inference and all probability-based modeling. Assuming a background in probability theory (developed as a Core Mathematics module, Section 7.2.1), this course introduces the basics of statistical inference and probabilistic methods in modeling and simulation.

In order to emphasize the modeling perspective and maintain focus on applications, we suggest a three-component structure for each of these modules; this structure consists of: (a) basic theory and pertinent mathematical results, (b) per-
spective on modeling by way of real-life contexts, examples and applications, and (c) relevant numerical methods.

<table>
<thead>
<tr>
<th>Module</th>
<th>Syllabus Section</th>
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<td>B.5.1</td>
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<tr>
<td>• Stochastic Simulation</td>
<td>B.5.2</td>
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<tr>
<td>• Stochastic Differential Equations</td>
<td>B.5.3</td>
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</tbody>
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Total Number of Contact Hours 45
Total Number of Credits 3

7.2.6 Perspectives on Probability Modeling II

Rationale and Outlook • Same as that of Section 7.2.5.

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<th>Module</th>
<th>Syllabus Section</th>
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<td>• Statistical Models and Methods</td>
<td>B.6.1</td>
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<tr>
<td>• Stochastic Optimization</td>
<td>B.6.2</td>
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</table>

Total Number of Contact Hours 45
Total Number of Credits 3

7.2.7 Practical Computing I

Rationale and Outlook • A solid background in basic software methodologies and technologies together with ample hands-on experience is highly necessary to be able to effectively utilize the perspective in modeling and simulation that are developed through the rest of the M&S programme.

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<th>Module</th>
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<td>• Truncated Numbers and Finite-Precision Arithmetic</td>
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<td>• Case Studies I</td>
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Total Number of Contact Hours 45
Total Number of Credits 3
7.2.8 Practical Computing II

Rationale and Outlook • Same as that of Section 7.2.7.

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<td>• Case Studies II</td>
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Total Number of Contact Hours 45
Total Number of Credits 3

7.3 Electives

Rationale and Outlook • Given the preparation of the first two trimesters and the core courses, a student is expected to be in a position to assimilate material from advanced, specialized, or domain-specific elective modules of his or her choice. These elective modules are expected to demonstrate applications of the concepts developed towards the construction of real simulations.

In this section, we simply list a number of possibilities for the electives; detailed syllabi will be developed as and when required:

• Simulations in Physics
• Materials and Molecular Modeling
• Introduction to M&S for Complex Systems
• Six Degrees of Separation: an Introduction to Networks
• Evolutionary and Agent-Based Modeling
• Quantum Computing
• Digital Signal Processing
• Monte Carlo Methods in Finance
• Neural Networks, Machine Learning and Data Mining

The elective is one full course (4 credits):

Total Number of Contact Hours 60
Total Number of Credits 4

Note that it may not be possible to offer the same set of electives every year. Whether a particular elective could be offered during a specific programme year depends on the availability of a domain expert in the respective domain.
7.4 The Project

Rationale and Outlook • Given the highly applied nature of the M&S Programme, it is natural to emphasize substantial hands-on project work. We thus propose

- to use an acceptability criterion for project work that is much higher than the standard University of Pune passing grade of C+.
- that project grade should be mentioned separately from the GPA for the rest of the course.
- that students be encouraged to look for and start preparing for their projects as early on during the M&S Programme as possible.

The project is considered equivalent to 3 full courses or 12 credits:

| Total Number of Contact Hours | 180 |
| Total Number of Credits       | 12  |

7.5 The Term Papers

Rationale and Outlook • In addition, in order to foster self-study skills, resourcefulness, independence, plus the ability to read technical and research literature and make presentations, a student is expected to present two term papers on a topic of his or her interest related to modeling and simulation. Evaluation of the term papers will be based on (a) the term paper/report itself, and (b) a presentation. The term papers are considered equivalent to 1 full course or 4 credits:

| Total Number of Contact Hours | 60  |
| Total Number of Credits       | 4   |

7.6 Evaluation and Grading

We recommend the following guidelines for student evaluation:

1. Adequate weightage to both “theory” and “practice” aspects.
2. Continuous evaluation throughout a programme year that aims at accurately assessing the knowledge, abilities and skills relevant to modeling and simulation acquired through the M&S programme. This may include, at the discretion of an instructor, class participation.
3. Periodic examinations consistent with existing University of Pune practices and patterns, yet designed to bring about the real knowledge, abilities and skills of a student.
A History and Credits

- An initial draft of this document emerged in mid-2004 out of close interactions, uncountable informal discussions, unique individual perspectives, and several formal meetings, between members of a core group at the Center for Modeling and Simulation (in reverse-alphabetical order: Vaishali Shah, Ajay Nandgaonkar, Sailaja Krishnamurty, D. G. Kanhere, P. M. Gade, Mihir Arjunwadkar) and two experts closely associated with the Centre (Abhijat Vichare, CFDVS, IIT Powai, and Ashutosh, Agilent Systems Pvt. Ltd., Pune).

- Abhijat Vichare, in particular, deserves a major part of the credit for defining and refining our outlook on simulation and modeling, and for contributing his own version of this document, parts of which have been incorporated almost verbatim in this document.

- Those who contributed syllabi for topics of their specialty or choice (in reverse-alphabetical order) are: Abhijat Vichare, Anagha Kuvalekar, Neeta Kshemkalyani, Sailaja Krishnamurty, P. M. Gade, Ashutosh, and Mihir Arjunwadkar. These have been incorporated in this proposal without alteration.

- In the process of designing the syllabi, some of us have consulted many online resources on the web, some of which have been cited under individual syllabi. The rest are too numerous to list: we acknowledge these with sincere thanks.

- Mihir Arjunwadkar coordinated the entire development of the M&S programme and the evolution this document.

- This document was sent for review and feedback to experts both from academics and industry. Those who responded and shared their views and insights with us are listed below, with our sincere thanks, in a reverse-alphabetical order:

  Abhijat Vichare (CFDVS, IIT Powai) • William Sawyer (Department of Environmental Sciences, ETH Zürich) • R. Sankarasubramanian (Defense Materials Research Laboratory, Hyderabad) • Mangesh Patwardhan (National Insurance Academy, Pune) • Abhay Parvate (Department of Physics, University of Pune) • Suhas Pansare (KPIT Pvt. Ltd., Pune) • Uttara Naik-Nimbalkar (Department of Statistics, University of Pune) • Rustom Mody (Department of Computer Science, University of Pune) • Subhash Ghaisas (Department of Electronic Sciences, University of Pune) • Anil Gangal (Department of Physics, University of Pune) • Ashutosh (Agilent Systems, Pvt. Ltd., Pune)
B Syllabus

1 We assume that the reader, at this point, is already familiar with all of the preceding sections of this document. The reader may, however, find it useful to refer to Section 7.1 that outlines our academic outlook, to Section 7.2 that provides an outline with justification for the modulewise syllabi provided in this section, and to Section 1 and 2 that summarize the entire M&S Programme in a succinct manner.

2 Here is the credit break-up for the entire M&S programme, plus a roadmap into this document:

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Total Number of Programme Credits 48

3 The actual order of presentation of individual modules below to the students would need to take into account modulewise dependencies and prerequisites.

4 Course codes assigned in this section are tentative at this stage. They are of the form CMS-M&S-\(t\)-\(c\), where \(t\) indicates the trimester in which the course is to be run, and \(c\) indicates, for the core courses, the course number under Section 7.2.
B.1 Core Mathematics (CMS-M&S-1-1)

B.1.1 Essentials of Analysis

Number of Lectures • 5
Prerequisites • None

Syllabus

Review of real analysis, (continuity, differentiability, limits of sequences and functions, integration)
Complex numbers, complex functions, limits and continuity Complex differentiation, analytic and harmonic functions, Complex integration, Line integrals, Cauchy theorem, Cauchy integral formula, Residues and applications, Taylor and Laurent series. Elementary overview of branch cuts(?).

Suggested Texts and References

Module contributed by P. M. Gade

B.1.2 Linear Algebra

Number of Lectures • 20
Prerequisites • None

Syllabus


Suggested Texts and References


Module contributed by Mihir Arjunwadkar

B.1.3 Probability Theory and Stochastic Processes

Number of Lectures • 20
Prerequisites • B.1.4(1,2)

Syllabus


4. Inequalities for Probabilities and Expectations.


Suggested Texts and References


B.1.4 Discrete Mathematics

Number of Lectures • 15

Prerequisites • None

Syllabus


Binomial and multinomial coefficients. $r$-permutations and $r$-combinations with repetition and limited repetition. Assorted examples and applications. Hall’s marriage theorem.


8. **More on Induction.** Applications of induction and other proof techniques to analysis of algorithms. Recursive definitions and structural induction.

9. **Elementary Number Theory.** Division, greatest common divisor, modular arithmetic, Chinese remainder theorem, factoring, Fermat’s little theorem, Euler’s theorem.

10. **Groups and Other Algebraic Structures.** Semigroups, groups, group isomorphism, cyclic groups, subgroups, Lagrange’s theorem. Symmetry and symmetry groups, symmetries as permutations, combining symmetries. Monoids, fields, rings, lattices, etc.

*Suggested Texts and References*


Module contributed by Mihir Arjunwadkar
B.2 Theory of Computation (CMS-M&S-1-2)

B.2.1 Theory of Computation

Number of Lectures • 20
Prerequisites • B.1.4

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.


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.

Suggested Texts and References

B.2.2 Programming: Theory and Perspectives

Number of Lectures • 25
Prerequisites • None

Syllabus


Suggested Texts and References


Module contributed by Neeta Kshemkalyani
B.2.3 Algorithm Design and Analysis

Number of Lectures • 15
Prerequisites • None

Syllabus


Suggested Texts and References

B.3 Perspectives on Mathematical Modeling I (CMS-M&S-1-3)

B.3.1 Modeling Change with Difference Equations

Number of Lectures • 7
Prerequisites • B.1.1

Syllabus

1. Introduction. Sequences and differences. Properties and applications of difference tables.
2. Modeling Change with Difference Equations. Perspective from applications in mechanics, population growth, population genetics, macroeconomics, ...
6. Sums and Series.

Suggested Texts and References


Module contributed by Mihir Arjunwadkar

B.3.2 Ordinary Differential Equations, Dynamics and Nonlinearity

Number of Lectures • 20
Prerequisites • None

Syllabus

Autonomous and non-autonomous first and second order non-linear differential equations (ie. vector fields), deterministic, stochastic...physical examples. Phase space, stability analysis, Poincare sections.

Linear and non-linear difference equations (ie. Maps), logistic, area preserving, Henon, Chirikov, routes to chaos, period doubling, quasiperiodicity and intermittency. Lyapunov exponent. Definition and numerical calculation.
Strange attractors (Quantifiers: Fractal dimension, topological entropy, information entropy).

Suggested Texts and References

B.3.3 Partial Differential Equations and Finite Element Methods

Number of Lectures • 20
Prerequisites • None

Syllabus


3. **Elliptic Equations in One, Two and Three Space Dimensions.**


Suggested Texts and References

B.3.4 Integral Equations

Number of Lectures • 7
Prerequisites • None

Syllabus
Integral equations, Fredholm integral equation of first kind, Fredholm integral equation of second kind, Volterra integral equation of first kind, Volterra integral equation of second kind, applications.

Suggested Texts and References

Module contributed by P. M. Gade

B.3.5 Calculus of Variations

Number of Lectures • 6
Prerequisites • B.1.1, B.1.2

Syllabus
2. Elements of Functional Analysis.
3. Applications in Mechanics and Optimal Control Theory.

Suggested Texts and References

Module contributed by Mihir Arjunwadkar
B.4 Perspectives on Mathematical Modeling II (CMS-M&S-2-4)

B.4.1 Transforms

Number of Lectures • 20
Prerequisites • None

Syllabus

Wavelet transform. Definition and applications.
Radon transform, Hough transform. Basic theory and applications.
Hilbert Transform.
An introduction to some other useful transforms. More emphasis on applications and salient features of different transforms which make them applicable in different cases. Less emphasis on proofs. However, student should be able to derive simple properties of transforms.

Suggested Texts and References

Boggess and Narcowich, A First Course in Wavelets with Fourier Analysis, Prentice Hall, 2001
Walnut, David F., An Introduction to Wavelets Analysis, Birkhauser Boston, 2001,

B.4.2 Optimization

Number of Lectures • 20
Prerequisites • None

Syllabus


**Suggested Texts and References**


Module contributed by Sailaja Krishnamurty

**B.4.3 Numerical Linear Algebra: A User’s Perspective**

**Number of Lectures** • 15

**Prerequisites** • B.1.2, B.7.1

**Syllabus**


Suggested Texts and References


Module contributed by Mihir Arjunwadkar
B.4.4 Miscellaneous Topics in Numerical Analysis

Number of Lectures • 5
Prerequisites • None

Syllabus

1. Miscellaneous topics in numerical analysis. Topics of practical importance that are not covered in any of the rest of the modules.

Suggested Texts and References


Module contributed by Mihir Arjunwadkar
B.5 Perspectives on Probability Modeling I (CMS-M&S-1-5)

B.5.1 Reasoning Under Uncertainty

Number of Lectures • 25
Prerequisites • B.1.3

Syllabus


Suggested Texts and References

B.5.2 Stochastic Simulation

Number of Lectures • 15
Prerequisites • B.1.3

Syllabus


Suggested Texts and References


Module contributed by Mihir Arjunwadkar
B.5.3 Stochastic Differential Equations

Number of Lectures • 5
Prerequisites • None

Syllabus Introduction to stochastic differential equations and its applications.

Suggested Texts and References
B.6 Perspectives on Probability Modeling II (CMS-M&S-2-6)

B.6.1 Statistical Models and Methods

Number of Lectures • 25
Prerequisites • B.5.1

Syllabus

3. Inference about Independence. Two binary variables. Two discrete variables. Two continuous variables. One continuous variable and one discrete variables.

Suggested Texts and References


Module contributed by Mihir Arjunwadkar

### B.6.2 Stochastic Optimization

**Number of Lectures** • 20

**Prerequisites** • B.5.2

**Syllabus**


8. Evolutionary Computation III: Particle Swarm Optimization.

9. Statistical Methods for Optimization in Discrete Problems. Statistical comparisons test without prior information. Multiple comparisons against one candidate: with known noise variance(s), with unknown noise variance(s). Extensions to Bonferroni inequality; ranking and selection methods in optimization over a finite set.


12. Introduction to Optimization Under Uncertainty. Optimization problems where some of the constraints include random (stochastic) components, such as online optimization under time constraints, stochastic load balancing and related problems, stochastic knapsack problem, stochastic combinatorial and discrete optimization problems, stochastic approaches to supply chain management problems.

Suggested Texts and References


Module contributed by Mihir Arjunwadkar
B.7 Practical Computing I (CMS-M&S-1-7)

B.7.1 Truncated Numbers and Finite-Precision Arithmetic

Number of Lectures • 3

Prerequisites • None

Syllabus


3. **Finite-Precision Arithmetic with Floating-Point Numbers.** How elementary arithmetic operations are performed. Subtraction and loss of precision. Illustrative examples.

4. **A User’s Perspective on IEEE 754.** The IEEE 754 specification. All about NaNs and Infs. Tracking floating-point exceptions. Outlook on IEEE 754.

Suggested Texts and References


B.7.2 Systems Modeling and Simulation

Number of Lectures • 15

Prerequisites • None

Syllabus


**Suggested Texts and References**


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**B.7.3 Programming Paradigms and Perspectives Hands-On**

**Number of Lectures** 10

**Prerequisites** None

**Syllabus**

1. **Types and variables** Representation of primitive types, arrays, disjoint unions, recursive types etc. Storage for global and local variables, heap variables
   Implementation of static and dynamic arrays
2. **Abstraction** Implementation of procedure calls, method calls Objects, Parameter Passing, Generic Units, Critical regions
3. **Type Systems and Control Flow** Implementation of polymorphic procedures
   Implementation of jumps and escapes, exceptions
4. **Paradigms** Case studies taking specific language examples for Imperative Programming Object-Oriented Programming Concurrent Programming Functional Programming Logic Programming Scripting

**Suggested Texts and References**

- See Texts and References for the Programming: Theory and Perspectives module, Section B.2.2.
B.7.4 Case Studies I

Number of Lectures • 17
Prerequisites • None

Syllabus

1. Hands-On Case Studies relevant to the *Perspectives on Mathematical Modeling I* (Section B.3) and *Perspectives on Probability Modeling I* (Section B.5) courses.

Suggested Texts and References
B.8 Practical Computing II (CMS-M&S-2-8)

B.8.1 High-Performance Computing

Number of Lectures • 20
Prerequisites • None

Syllabus

1. Performance issues and measurement Profiling and development tools Sustained versus peak performance
2. High performance sequential computing Effects of the memory hierarchy Out-of-order execution superscalar processors
3. Vector processing
4. Shared-memory processing Architectures (extensions of the memory hierarchy), Programming paradigms, OpenMP
5. Distributed-memory processing Architectural issues (networks and interconnects), Programming paradigms, MPI (+MPI2)
6. Grids Computational grids, Data grids
7. Performance libraries and packages

Suggested Texts and References


B.8.2 Case Studies II

Number of Lectures • 25
Prerequisites • None

Syllabus

1. Hands-On Case Studies relevant to the Perspectives on Mathematical Modeling II (Section B.4) and Perspectives on Probability Modeling II (Section B.6) courses.

Suggested Texts and References
B.9  Elective (CMS-M&S-2-9)

Number of Credits • 4

Syllabus for the Electives will be developed as and when required, depending on the electives offered during a programme year; see Section 7.3.

B.10  Project (CMS-M&S-3-10)

Number of Credits • 12

See Section 7.4.

B.11  Term Papers (CMS-M&S-3-11)

Number of Credits • 4

See Section 7.5.