DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY BOMBAY
EE 338: DIGITAL SIGNAL PROCESSING: COURSE OUTLINE
Spring Semester: Jan-Apr 2025

Prelude to the course:

The advent of modern computers has implied a dramatic increase in computational power and computational resources. This has enormous implications for signal processing: which is the science and art, by which we extract information from signals and modify them. The current scenario has led to the development of certain signal processing tools, which were unheard of, when processing was purely analog. Further, such tools are easily amenable to modification and upgradation. In all this development, however, it has been necessary to adopt one fundamental change in the modus operandi of processing signals, which is as follows. Analog processing inherently works with a continuum of values for the independent variable. On the other hand, for the best possible use of computational resources available today, the independent variable must be discretized. If the independent variable is time, for example, one needs to deal with a series of data indexed by discrete points in time.

Over the last quarter of the twentieth century, this subject of dealing with discrete data has evolved tremendously. It is formally termed "Digital Signal Processing" (DSP). Tremendous research has gone into building the subject up to its current status. It has myriad applications. The areas of application include, but are not limited to: data communication, audio and video compression, instrumentation, active noise control, geophysical system analysis and design, biomedical signal and system analysis, wireless communication systems…in fact, the domain of application of Digital Signal Processing is growing day by day. Research and development in this field continues even to date.

In the currently ongoing first quarter of the twenty first century, the subject of Digital Signal Processing has, again, grown from strength to strength. Many specialized subjects have emerged from the fundamental foundations laid in Digital Signal Processing. These include, but are not limited to: adaptive signal processing, multirate and multi-resolution signal processing, multidimensional signal processing, nonlinear signal processing. There are also several application domains, which have grown into subjects by themselves: which, again, include but are not limited to: biomedical signal processing, signal processing for communication, image processing and computer vision.

The aims of this course are as follows:

(i) To understand the basic principles that form the foundation of this rich and evergreen subject.

(ii) To provide some expertise in traditional DSP system design and realization, with emphasis on standard discrete time filters.

(iii) To inculcate a joint view of signal processing and machine learning, by exploring some elementary principles and developments in this joint domain.

(iv) To study at least one application of Digital Signal Processing in some detail.

Philosophy behind the course content and evaluation policy:

In the past offerings of the undergraduate versions of the course, as expressed by students, themselves, in the course feedback, the teaching of fundamental discrete time system principles was seen as repetitive and unnecessary, given that a first course had already been completed on those principles. Accordingly, in this offering, the teaching of these fundamental principles has been truncated and expedited, to make way for introducing advanced topics: as, for example: multidimensional signal processing, multirate signal processing and digital signal processing architectures. Further, it is important for all engineers and scientists working in the domain of signal processing, to appreciate the revolution brought in, by machine learning and deep learning. Many foundations of machine learning actually lie in signal processing. Witness, for example, the class of convolutional neural networks (CNNs). In this course, we also intend to initiate the student into this joint domain, of signal processing brought together with machine learning and deep learning.

As far as evaluation of student performance is concerned, it is important to recognize the need of a student, to **earn a minimum pass and/or interim grade** for, what can be seen, as minimally adequate class participation and demonstrated minimal competence in the course material. At the same time, **the best grades** should only be earned by students who make that extra effort and/ or 'go that extra mile' to learn, contribute and demonstrate competence. The evaluation policy in this course respects these complementary needs.

COURSE OUTCOMES:

Necessary outcomes: The student must be able to:

1. Identify correctly whether a discrete system obeys the basic system properties of linearity, shift-invariance, causality and stability, with appropriate reasoning. This should be done both, for one-dimensional and multi-dimensional discrete signals, as applicable.
2. Analyze discrete system behaviour correctly in the Discrete Time Fourier Transform Domain, if admissible, for elementary situations. This should be done both, for one-dimensional and multi-dimensional discrete signals.
3. Analyze discrete system behaviour correctly in the z-Transform Domain, if admissible, for elementary situations.
4. For one-dimensional discrete signals: Design Infinite Impulse Response (IIR) Filters with given realizable specifications, taking assistance of programming and numerical tools, using the bilinear transformation and frequency transformations, based on the Butterworth and, preferably also, Chebyschev approximations for IIR Filter Design.
5. For one-dimensional discrete signals: Design Finite Impulse Reponse (FIR) Filters with given realizable specifications, taking assistance of programming and numerical tools, using the window method.
6. For one-dimensional discrete signals: Realize discrete systems using, at least, Direct Form – I, II and Cascade-Parallel Forms.
7. For one-dimensional discrete signals: Use the Discrete Fourier Transform (DFT) at an elementary level, to analyze discrete time systems, when admissible.
8. Write out a radix-2 Fast Fourier Transform (FFT) algorithm using decimation in time and decimation in frequency and evaluate it for computational complexity.
9. Describe and explain in reasonable detail, at least one practical application of Digital Signal Processing, with sound technical details. We may, this time, choose to streamline the application areas, in which we explore such applications.

Examples of Extraordinary Outcomes: If the student does one or more of the following, these would be considered as above average achievements.

10. Extend IIR and FIR Filter Designs to more paradigms, than the basic ones recommended, as, for example, Elliptic Filter Designs and carry out such designs with a comparison.
11. Realize and demonstrate synthesis of Digital Signal Processing (DSP) systems, with visible and evident practical applications, particularly keeping the National Semiconductor Mission in perspective. Identify connections between DSP and VLSI.
12. Contribute to the pedagogy of the course in consultation with the instructor and/or assist the instructor in designing the pedagogy of this, or proposed/ related courses. In particular, expound on the depth and breadth of the possibilities of unifying machine learning/ deep learning with digital signal processing, as a part of this course and/or assist the instructor in designing such a course, as a follow up to this course, in the future.
13. Address a research problem, which shall be open to the class, explained by the instructor.

Proposed course outline:

This is only indicative and suggestive - more like a guideline. It could be dynamically adapted, to suit the response and requirements of the class.

1. Analog to digital conversion: moving from the continuous independent variable to the discrete independent variable: (*likely to have been taught in the earlier course(s), hence a speedy recapitulation will suffice; some topics are new – the multidimensional extensions*)
    i. The sampling theorem and its consequences: uniform and non-uniform sampling
    ii. Aliasing and its manifestation
    iii. Correlating the analog and discrete time domains
    iv. Discretization of the dependent variable (quantization): distinction from sampling
    v. Formalizing the notion of a discrete sequence and a discrete system. Examples of prototype discrete systems.

vi. Difference equations and their solutions

vii. Multidimensional extensions (could be brought in later), which are particularly important for machine learning/ deep learning for image/ video.

2. Discrete time systems and their characterizing properties: (*likely to have been taught in the earlier course(s), hence a speedy recapitulation will suffice; some topics are new – the multidimensional extensions*)

    i. Linearity, shift-invariance, memory, causality, stability, realizability and other related system properties.

    ii. Linear shift-invariant (LSI) systems and their importance.

    iii. The impulse response and its role in characterizing LSI systems.

    iv. Linear difference equations, linear constant coefficient difference equations and their solution (LCCDEs).

    v. The relation between LCCDEs and LSI systems

    vi. Eigenfunctions and eigenvalues of systems. The role of the sinusoid and the complex exponential.

    vii. Frequency response and its meaning.

    viii. The Convolutional Neural Network (CNN) as an important nonlinear system and predominant component, for machine learning.

    ix. Discrete Multidimensional extensions (could be brought in later), which are particularly important for machine learning/ deep learning for images and video.

3. Frequency Domain Analysis for Discrete Time Systems: (*likely to have been taught in the earlier course(s), hence a speedy recapitulation will suffice; some topics are new – the multidimensional extensions*)

    i. The notion of discrete system frequency response in more detail

    ii. The Discrete Time Fourier Transform (DTFT) and its properties

    iii. The existence of a frequency response for LSI systems

iv. Relation between the impulse response and frequency response

v. Discretization of the frequency response: the Discrete Fourier Transform (DFT)

vi. Going back and forth between discrete time (independent variable) and discrete frequency: time domain and frequency domain aliasing

vii. Frequency selective systems and filters

viii. Energy/ Power Spectral density

ix. The Parseval's Theorem: specific statement for the frequency domain, its interpretation

x. Discrete Multidimensional extensions (could be brought in later): which are particularly important for machine learning/ deep learning for images and video

4. The generalized eigenfunction domain (z-domain) and its use: (*likely to have been taught in the earlier course(s), hence a speedy recapitulation will suffice; some topics are new – the multidimensional extensions*)

i. The z-transform and the inverse z-transform

ii. The z-transform as a generalization of the DTFT

iii. Methods for forward and inverse z-transformation

iv. Region of convergence (ROC) and its implications.

v. Rational and irrational systems.

vi. LCCDEs revisited: rational transfer functions

vii. Poles and Zeros: their significance and relation to system properties: stability, causality.

viii. Z-transforms and DTFTs: interrelationship, role of pole-zero configuration.

ix. Minimum and non-minimum phase systems.

x. Contour integration for inverse z-transformation and the generalized form of Parseval's Theorem.

xi. The relation between system realization and the transfer function: DSP components

xii. Discrete Multidimensional extensions (could be brought in later)

5. Digital Filters and their general characteristics:

    i. Magnitude and phase responses, specifications for discrete systems: ideal frequency responses

    ii. Unrealizability of the ideal and the need to approximate

    iii. Finite and infinite impulse response systems: advantages and disadvantages

    iv. Phase response: phase and group delay

6. Infinite Impulse Response (IIR) Filters and their design:

    i. Why IIR filters? Advantages and disadvantages.

    ii. Design from analog prototypes: mapping from s-plane to z-plane: the bilinear transformation

    iii. Lowpass IIR filers: the Butterworth and Chebyschev approximations

    iv. Frequency Transformations.

    v. Generalizations to highpass, bandpass and bandstop filters.

    vi. A brief introduction to other methods of filter design.

7. Finite Impulse Response (FIR) Filters and their design:

    i. Why FIR filters? Advantages and Disadvantages.

    ii. Windowing and the design of FIR filters using windows.

    iii. Odd-length and even-length FIR filters.

    iv. Optimum FIR filter design: equiripple filters and Park-Mc Clellan's algorithm.

    v. The frequency sampling method of FIR filter design.

8. Realization of Discrete Time systems – particularly important for the connection between Digital Signal Processing and the National Semiconductor Mission:

i. Realizability (finite average computation per output sample) and rationality
ii. Components in realization: multipliers, adders, delays
iii. Hardware for DSP systems: special features/ dedicated systems
iv. Direct Form I and II realizations
v. Cascade and Parallel Realizations
vi. The lattice structure and its importance
vii. Ladder forms
viii. Signal Flow Graphs and Mason's Gain Formula
ix. Low sensitivity structures based on all-pass filters: exposure

9. The Discrete Fourier Transform (DFT) and its efficient computation, through Fast Fourier Transforms (FFTs):
   i. Sampling the normalized discrete system frequency axis and its consequences: time domain aliasing
   ii. The notion of decimation and partitioning in time and frequency.
   iii. FFT algorithms for a power-of-two number of points N.
   iv. FFT algorithms for composite N, in general
   v. Spectral analysis of real-life signals and the FFT
   vi. Linear convolution and circular convolution: relationship to the FFT.
   vii. Discrete Multidimensional extensions (could be brought in later)

10. Further Advanced topics in DSP: (as time permits and need demands)
   i. Convolutional Neural Networks (CNNs) – Unifying Signal Processing and Machine Learning/ Deep Learning by looking at a class of nonlinear and/or shift-variant systems: Deeper Analysis
   ii. VLSI and Digital Signal Processing
   iii. Further principles of Multidimensional DSP
   iv. Multirate Digital Signal Processing and Wavelets
   v. Homomorphic methods
   vi. Spectral estimation and its methods

NPTEL Resources For This Course:

For this course, we have the following NPTEL resource in the background:
NPTEL Site: https://nptel.ac.in/courses/108/101/108101174/
This is the available NPTEL course, created through the lectures given by the instructor himself and augmented by erstwhile students in this course, from IIT Bombay and two other Institutes, GHRCoE, Nagpur and PVGCoET, Pune: Please use the following link to access the course "Digital Signal Processing and its Applications", which is available on the NPTEL website anytime. **The course is also running in 'Repeat Mode' on NPTEL during the semester and those students who would like to assist in the pedagogy of the 'Repeat course' are welcome. Their pedagogical participation, if substantive, shall be recognized as an 'extraordinary outcome' in this course.** Students are welcome to, actually encouraged to, make use of these NPTEL resources, to supplement the classroom lectures.

Conduct of the course and evaluation policy:

The course includes three contact hours per week, some of which will serve as tutorial sessions or problem-solving sessions.

Award of marks and grades

The following are the mandatory components of student engagement in the course. Doing well in these components is necessary, for earning a good grade in the course.

1. **Mid Semester Examination: 30 percent weight (60 marks).**
   This examination may be a combination of a 'take-home' component and an 'on-site' component, or, exclusively one of these. The final form will be announced in time. The take-home component is likely to be based on a filter design problem.

2. **In-semester class participation: 30 percent weight (60 marks)**
   In-semester class participation will have the following **sub-components**:
   (a) **Announced or unannounced class tests** may be conducted, for integer **multiples of 10 marks**, during the regular classes. **Students must, on their own, regularly carry proper stationery** to answer these class tests: good quality paper, writing

instruments, a stapler to affix multiple sheets and a non-programmable calculator. Students earn marks **individually** for this component. There shall be **at least two** such class tests. If there are more than two, then the best two class test performances shall be considered for each student. These class tests, thus, earn up to 20 marks for a student, on individual basis.

(b) **Group Activities:** Students will form **groups of up to three students in a group and do the following**, as a group. Students may kindly form their groups and announce the same, on the group formation forum on Moodle. Groups are expected to carry out the **following activities** in the course:

(i) **Solve tutorial problems.** Each group shall be permitted to put up reasonably complete attempts, to, **up to four tutorial problems posed/ designated, as such, by the Instructor and/or the Teaching Associates**. **Each** reasonable attempt to a tutorial problem earns **up to 5 marks**. A group is permitted to attempt only two tutorial problems before the mid-semester examination and two tutorial problems after the mid-semester examination, up to a cut-off date, two weeks before the last date of instruction. All of these marks will be awarded to **each of the group members**, agnostic of group size. A solution to each tutorial problem posed in the course, may be put up by **up to three groups**, again *without copying from one another*. The solutions to tutorial problems must be as distinct as they can be, when multiple groups attempt the same problem(s). Tutorial problem solutions can, thus, earn each member of a group, up to 20 marks.

(ii) **Solve challenge problems.** Each group shall be permitted to put up reasonably complete attempts, to **up to two challenge problems posed by the instructor**. **Each** reasonable attempt to a challenge problem earns **up to 10 marks**. A group is permitted to attempt only one challenge problem before the mid-semester examination and one challenge problem after the mid-semester examination, up to a cut-off date, two weeks before the last date of instruction. All of these marks will be awarded to **each of the group members**, agnostic of group size. A solution to each challenge problem posed in the course, may be put up by **up to three groups**, again *without copying from one another*. The solutions to challenge problems must be as distinct as they can be, when multiple groups attempt the same problem(s). Each group may also **replace one of these two permitted challenge problem attempts by one short note,** on an idea which they have come up with, on what is taught in the course, **beyond what was discussed in the class**, expressed in their own words. For example, it can be related to **applications of digital signal processing**, beyond what were discussed during the classes. **Each such idea presented must be distinct**. This earns 10 marks, akin to the challenge problem(s) solved. Each member of each group can, thus, earn up to 20 marks in the class participation component, for challenge problem/ idea submission**.**

3. **Semester End Examination: 40 percent weight (80 marks)**
   This examination may be a combination of a 'take-home' component and an 'on-site' component, or, exclusively one of these. The final form will be announced in time. The take-home component is likely to be based on a filter design and realization problem.

Total of the above: 200 marks.

Extraordinary Efforts:

Students are encouraged to participate in one or more of the extraordinary effort opportunities listed in the sequel. There is **no compulsion** to participate in any of them, but meaningful participation, in one or more of these activities, is likely to be rewarded in terms of credit earned for the award of grades in the course and/ or in some other manner, depending upon the contribution and accomplishment of the student(s) concerned. Further, the participation of the class, as a whole, in these extraordinary efforts, will give the Instructor and the Teaching

Associates, a sense, of how keen the class is, to learn this course in some depth, beyond only what is prescribed. Naturally, that influences the overall grading policy in the course.

Given the large academic commitments of students in other courses, the participation in these extraordinary efforts should be balanced, to keep good physical and mental health and, also, to maintain the joy of participation, not letting it become an insurmountable burden and/or a cause to rant and rave about too much work to do. Students may participate for these extraordinary efforts individually, or in groups, both during and after completion of the current course. They could work in the same groups as for the mandatory components, or in different groups, for these additional opportunities. The students who work together, in a group, for one or more of these activities, should announce their association as a group clearly, for each of these activities participated in.

4. **Study and present material pertaining to the union of signal processing and machine learning/ deep learning/ neural networks**. The modus operandi for this component, will be explained in more detail, in an exposition by the instructor. In particular, this component intends to look at the signal processing aspects of machine learning/ deep learning/ neural networks structures; particularly emphasizing explainability, interpretability and economy. The aim of this component is, also, to assist the instructor in designing a course around this union theme, as a follow up to this course and an independent course, in its own right, in the future.

5. Reasonable attempt to the **Optional parts of the Filter Design Assignment.** The group can work together for this component and members may assist one another.

6. Study, experiment, innovate and design demonstration systems: around open-source FPGA Resources, pertaining to the **connection between Digital Signal Processing (DSP) and the National Semiconductor Mission of India**. This would imply working towards possibilities of FPGA Implementation of DSP Structures, realization of DSP specific architectures, union of DSP and VLSI.

7. **Some more opportunities, if announced; or efforts of students recognized,** by the instructor in the course, for class participation or **appreciation of some extraordinary contribution** by one or more groups/ individuals. For example, assisting the instructor in the conduct of the Repeat Mode NPTEL course running from Jan – Apr 2025.

Attendance Policy: The instructor believes that **attendance in classes is very important** and cannot be compromised, in general, other than for genuine exigencies. **The instructor *may* institute negative marks for marked absences** or **positive marks for attendances on days, when the attendance is very thin** in the class, if he notices such a trend among student(s) in the class. These negative or positive marks shall be applied in the Class Participation Component of the evaluation scheme.

Instructor:

Dr. Vikram M. Gadre, Professor, Department of Elect. Engg.:
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Email address: vmgadre@ee.iitb.ac.in
Please feel free to contact the instructor personally and/or interact with him.

A LIST OF SOME REFERENCE BOOKS/ TEXTBOOKS ON DIGITAL SIGNAL PROCESSING:

1. Alan V. Oppenheim, Ronald W. Schafer – "Discrete Time Signal Processing", Prentice Hall of India (Private) Limited, New Delhi, 1994 (c1989). This book was earlier entitled "Digital Signal Processing" and one may consult/ use this earlier version if the current title is unavailable.
2. John G. Proakis, Dimitris G. Manolakis – "Digital Signal Processing – Principles, Algorithms and Applications", Third Edition, Prentice Hall of India Private Limited, New Delhi – 110 001, 1997, Eastern Economy Edition. An excellent text with a very detailed explanation of ideas. Develops the subject very thoroughly with a

comprehensive set of solved examples. A subsequent (fourth) edition of the book is also available in Eastern Economy Edition now.

3. Sanjit K. Mitra, "Digital Signal Processing – A computer based approach", Mc Graw Hill International Edition, Second Edition, 2001, Electrical Engineering Series. This book is likely to be available as a Tata Mc Graw-Hill Edition too. An excellent textbook and reference book. It deals with an extensive set of applications, problems and builds concepts very firmly.
4. Sanjit K. Mitra, "Digital Signal Processing Laboratory using MATLAB", Mc Graw Hill International Edition, 2000, Computer Science Series. A good laboratory supplement to a theory course.
5. James H. McClellan, Ronald W. Schafer, Mark A. Yoder, "DSP First: A Multimedia Approach", Prentice Hall, NJ, (c 1998 by Prentice Hall). Blends theory and application examples nicely.
6. Vinay K. Ingle, John G. Proakis, "Digital Signal Processing Using MATLAB", (c 2000 by Brooks/Cole), Brooks/Cole Publishing Company, a division of Thomson Learning. A good laboratory supplement to a theory course.
7. Monson H. Hayes, Schaum's Outlines of Theory and Problems of Digital Signal Processing, Mc Graw Hill Publishing Company, (c 1999). Provides a number of solved examples.
8. David J. De Fatta, Joseph G. Lucas, William S. Hodgkiss, "Digital Signal Processing- A System Design Approach", John Wiley and Sons, Inc. Pte. Ltd., Singapore. A good book from an applications perspective, with system design with DSP emphasized.
9. Johnny R. Johnson, "Introduction to Digital Signal Processing", Prentice Hall of India Private Limited, New Delhi – 110 001, 1994, Eastern Economy Edition. A lucid, introductory text with an excellent treatment for beginners. Also has good solved examples.
10. Lawrence R. Rabiner, Bernard Gold, "Theory and application of Digital Signal Processing", Prentice Hall of India Private Limited, New Delhi – 110 001, 1993, Eastern Economy Edition. This book would serve as a detailed reference for filter design. It may not be suitable as a text, for want of exercises to solve.

11. Thomas J. Cavicchi, “Digital Signal Processing”, John Wiley and Sons (Pte.) Limited: available in inexpensive Indian Edition. A fairly detailed and insightful text.
12. Jonathan (Y) Stein, “Digital Signal Processing – A Computer Science Perspective”, Wiley Student Edition, John Wiley and Sons (Asia) Pte Ltd. Available in inexpensive Indian Edition. It gives some reasonably detailed descriptions of applications, and architectures for Digital Signal Processing.
13. Avtar Singh, S. Srinivasan, “Digital Signal Processing – Implementations Using DSP Microprocessors with Examples from TMS320C54xx, Thomson Brooks/ Cole, Copyright 2004, ISBN: 981-243-254-4. This reprint is for sale in the Indian Subcontinent only. It is a very useful text to proceed from theory to design and implementation of systems on digital signal processors.

In addition, there are many other useful and well-written books by Indian and foreign authors. The above is meant to be a representative list.

ONLINE COURSE RESOURCES AND PLATFORMS:

The online interaction in this course shall be conducted in the ‘**M S Teams**’ Platform, with an M S Team dedicated to this course. In addition, it shall be a practice to utilize the web facility called “**Moodle**” in IIT Bombay for this course, to make announcements and disseminate information. Electronic course material will be made available, as and when needed, using a combination of the **M S Team of the course and the Moodle Site of the course**. Students must make it a point to refer to this M S Team and the Moodle site regularly, for announcements, instructions and other important information and documents. Student performance records will also be displayed there.

In addition, we shall explore the possibility of maintaining an additional departmental website at the address, only if needed. It may not be required, in normal course.

http://sharada.ee.iitb.ac.in/~ee603/

Further, recorded lectures for this course from a previous academic year, are available on the website of the Centre for Distance Engineering Education (CDEEP), IIT Bombay for reference and use by students.

We may also occasionally use ‘Google Meet’, if required.

Welcome to the beautiful world of Digital Signal Processing !