Advanced Digital Signal Processing (18-792)
Fall Semester 2024
Department of Electrical and Computer Engineering

PRELIMINARY SYLLABUS FOR FALL 2024

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Teaching assistants:

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General course support: Course support for things like handouts, homework and exam solutions, etc., will be handled at the ECE Academic Service Center, HH 1113. The website for the ASC is `https://www.ece.cmu.edu/academics/academic-services-center.html`.

Overview of the course: This course is a second course in one-dimensional digital signal processing that will introduce a number of topics of current importance in research and industry. The course will include a unified treatment of modern spectral estimation techniques, linear prediction, and adaptive filtering, along with discussions about related topics including multi-rate DSP, short-time Fourier analysis, wavelet processing and adaptive array processing. Many of these topics will be based on different types of optimum signal processing methods using least-squares estimation concepts and Wiener filtering.

Most of the topics discussed in 18-792 concern techniques of statistical signal processing, so students are expected to have already completed a basic undergraduate course in applied probability as well as a first course in digital signal processing. Background material in stochastic processes will be reviewed before the material is covered in depth.

To the extent possible, homework assignments in 18-792 will be dominated by a series of project assignments in which students implement and analyze the various signal processing algorithms discussed in class in MATLAB . Homework will be turned in online using Gradescope, and executable MATLAB code will be turned in online as well.

Major Educational Objectives (with relation to Course Outcomes):

- (a) an ability to apply knowledge of mathematics, science, and engineering: ADSP concerns the application of contemporary techniques in signal processing and statistical analysis to solve practical problems in engineering.
- (c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability: the ADSP homework assignments include major design components, with attention paid to issues such as processing time, storage, and computational complexity.
- (j) a knowledge of contemporary issues: the techniques used in ADSP are among the current state-of-the-art as practiced by leading professionals in the industry.
- (k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice: ADSP makes extensive use of the latest engineering algorithms, as well as the most popular engineering design tool for signal processing, MATLAB .

Prerequisites: 18-491/691 and 36-217, or consent of the instructor. MATLAB (or possibly Python) programming experience is necessary to complete the project assignments. While undergraduates who have completed 18-491/691 and 36-217 are encouraged to consider taking this course, we note that it will be taught as a graduate-level course rather than as a senior-level course. Students will be expected to work at a higher level of intensity than in undergraduate courses.

Class times and rooms: Lectures are Mondays and Wednesdays, 2:00 to 3:50 in WeH 4625. Recitations are Fridays 10:00 to 11:50 in PH 125B. The major focus of the recitations will be to discuss practical problems, and especially to review useful techniques for completing the following week's homework assignment. Occasionally the recitation and lecture days may be interchanged.

Attendance expectations: This semester we will be expecting that you attend classes in person. The lectures will be recorded on Zoom, for offline access after the lectures. The zoom recordings are not intended to be a replacement for in-class attendance. The notes from each lecture **will** be made available promptly on the course website. If COVID returns, we will make special arrangements to get lecture material and course notes to students who must isolate after testing positive for the virus, as needed. Please contact the Instructor (*i.e.* me) if special problems arise.

Attendance for all classes, including recitations, is highly recommended! It will make a big difference in your absorption and mastery of the course material.

Primary reading material: The selection of a textbook for an advanced topics course like 18-792 is more difficult than it is for a basic DSP course such as 18-491, as the choice of topics and style of presentation of the material vary far more from instructor to instructor. We will be using the following sources as your primary texts:

- Selected chapters from the edited book *Advanced Topics in Signal Processing*, edited by Jae S. Lim and Alan V. Oppenheim (Prentice-Hall, 1987). This resource will be used for our

discussions on multi-rate DSP, short-time Fourier analysis, and adaptive filtering. Although Lim (LO) has been out of print for years (with no hope for revival), it will be duplicated (with the permission of the publisher) and distributed to students in this class at no cost.

- The text *Discrete-Time Signal Processing, Third Edition*, by A. V. Oppenheim and R. V. Schafer (Prentice-Hall 2010)). This book is familiar to many of you as it has been the text for 18-491 in recent years. OSYP will be used as the text for classical sampling and elemnemtary stochastic processes.

- The book *Theory and Application of Speech Processing*, Rabiner, L. R. and Schafer, R. W. (2010), Pearson Press, will be the primary source for linear prediction.

- In addition to the sources cited above, we are also providing a complete set of lecture notes that were originally compiled and edited over the summer of 2020. These notes, which presently have the prosaic title *Selected Topics in Advanced Digital Signal Processing*, are available online in .pdf form at

  `http://www.ece.cmu.edu/~ece792/handouts/Notes_ADSP.pdf`

  Currently the last chapter on adaptive arrays is incomplete, but it is being actively rewritten and will be in better shape by the time we get to the end of the semester. If the notes ever stabilize (no promises here!), they will also be available optionally in hardcopy book form for the cost of publication and shipping. These notes are no more than a condensed prose transcription of what I present in class. They do not provide anything close to the context that is available from reading the original sources, which are identified at the beginnings of each chapter, and they are not guaranteed to provide all the information that is in the original lectures. Hence, these notes should be considered to be a supplement to, rather than a replacement for, the original lectures and the primary text material. Nevertheless, students in this class over the past several years have found them to be useful.

All required reading will also be available online, except for the DSP text by Oppenheim, Schafer, Yoder, and Padgett, which I assume you already have access to from previous courses.

Secondary reading material: For students who would like to consult other sources, the following books are recommended as well:

- **Comprehensive coverage of advanced digital signal processing and applications**

  1. *Statistical and Adaptive Signal Processing*, Manolakis, D. G., Ingle, V. K., and Kogon, S. M. (2005), Artech House Publishers. This is an excellent comprehensive review of statistical signal processing techniques that are covered in this course.
  2. *Statistical Digital Signal Processing and Modeling*, Hayes, M. (1996), Wiley. This is another excellent and comprehensive review. It is currently out of print, but used copies are available on Amazon.com.
  3. *Advanced Digital Signal Processing*, Proakis, J. G., Rader, C. M., Ling, F., and Nikias, C. L. (1992), Macmillan. This book covers similar ground as that of Lim and Oppenheim, with somewhat better coverage of linear prediction. Unfortunately, it is also out of print.

- **Power spectral estimation**

  1. *Digital Spectral Analysis with Applications*, Marple, S. L. (1989), Prentice-Hall, is an intuitive, practical treatment of the material, again out of print but available via Amazon.com.
  2. *Modern Spectral Estimation: Theory and Application*, Kay, S. M. (1999), Prentice-Hall, is more thorough and mathematical than Marple's text.

- **Signal processing for speech applications, including short-time Fourier analysis and linear prediction**

  1. *Theory and Application of Speech Processing*, Rabiner, L. R. and Schafer, R. W. (2010), Pearson.
  2. *Discrete-Time Signal Processing of Speech: Principles and Practice*, Quatieri, T. F. (2001), Pearson.

  The former book is an updated version of the classic text on speech processing. The latter book covers similar ground from a slightly different point of view. Both books also contain excellent treatment of a number of other one-dimensional signal processing techniques.

- **Adaptive filtering and adaptive array processing**

  1. *Adaptive Signal Processing*, Widrow, B. and Stearns, S. D. (1985). Prentice-Hall. This is a good introductory treatment of adaptive filtering and adaptive array processing.
  2. *Adaptive Filter Theory (5th Edition)*, Haykin, S. (2013), Prentice-Hall. This is the latest in texts by Haykin on this subject. The presentation is more rigorous and comprehensive and less intuitive than that of Widrow and Stearns.

Homework: Problem sets will usually be released by Thursday evening of each week. They will be discussed extensively (along with useful hints on how to solve the problems) on the Friday the morning after, and are generally due to be turned in via Gradescope by Friday at 0100 EDT/EST of the following week. The lowest homework grade will not be included in the final grade computation, as was noted above. In addition, to provide additional flexibility in dealing with surges in competing demands on your time, we will accept up to five additional late submission days over the course of the semester, with a maximum of two such late days available per assignment. Questions about the homework will be answered during the office hours of the following week

A significant component of the homework will be computer assignments using MATLAB . We have found that students benefit highly from having individual access to MATLAB . A site-licensed version of MATLAB can be downloaded from the CMU Andrew software site. Students will also have the option of allowing students to complete these assignments in Python, although the documentation and support for Python is not as complete and is not guaranteed to cover everything.

Late homework policy: In addition to our dropping the lowest homework grade (which of course means that you can opt out completely of one homework assignment during the semester), we will allow each student five (5) free late days, each carrying a deadline extension of 24 hours, with a maximum of two (2) for each assignment. After the "free" late days are used, the grades for late homework will be discounted according to how many days each assignment is late.

An encouraging note: This is one of those rare courses where students tell us on the FCEs that they actually enjoy working the homework problems!

Office hours: Each of the three of us on the teaching team will be available for two hours per week for office hours. Based on prior experience, we currently plan to have one office hour on each of Monday and Tuesday, and two office hours on Wednesday and Thursday. Times will be based on a quick poll of student availability.

Examinations: There will be two in-class exams on October 9 and November 20, plus a final exam during the regular final exam period, at a date to be announced later in the semester. Please arrange your other commitments so as not to conflict with these dates. Make-up exams will not be given unless there are extremely compelling reasons.

Grades: Grades will be based in part on performance in two or three examinations (nominally 55-65% of the final grade) and the homework and project assignments (35-45%). The lowest homework assignment grade will be excluded from the final grade calculations and the final exam will be weighted 1.5 times each midterm exam.

18-792 home page: We will be maintaining a home page for 18-792 which may be accessed through the URL `http://www.ece.cmu.edu/~ece792/`.

We will be putting all course handouts (with the exception of homework and exam solutions), reference documents, and other information on the 18-792 home page. The pages will also include the MATLAB scripts used for classroom demos and other material presented in the lectures. We will be using the Canvass site for grade reporting, using Piazza for discussions, and Gradescope for homework submission.

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A word or two about diversity and inclusion

The engineering profession has historically been one of the primary means by which people from humble origins, as well as members of minority groups, have been able to advance their social and economic status circumstances. Lamentably, in this country and around the world, people over the years have suffered from discrimination on the basis of their race, religion, ethnic origin, sexual preference, gender identity, and disability, along with a ton of other circumstances that I am probably not thinking of as I write this. The multiple killings of people of color by various police officers during the spring of 2020 has highlighted the extent to which endemic bias and discrimination can and does have lethal consequences. Nevertheless, it is the implicit bias that shades many of our day-to-day interactions that is more likely to affect many of us on a more ongoing basis.

It is our challenge and responsibility as engineers to support everyone with whom we work with and live, regardless of race, ethnicity, or other circumstance, and to treat everyone the same, based on merit alone. The tragedies of Spring 2020, which of course continue to this day, have sparked

a useful conversation, although fundamental change remains quite difficult and elusive. Let us all strive to work toward constructive change both at the societal level and in our day-to-interactions with each other.

One response to the George Floyd murder in 2020 and similar killings over the years has been the establishment of programs at all levels of our University to address and hopefully ameliorate these endemic problems at least to some degree. The ECE Diversity, Inclusion, and Outreach Committee has worked for a number of years to support all of our communities and to identify issues that come up in our own classes and research programs.

`https://www.ece.cmu.edu/student-resources/dio.html`

Please contact us at any time with suggestions on how the DIO committee can better serve our Department.

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Academic stress and sources of help

This course, along with many others at CMU, can be extremely demanding. Because of these pressures, the Provost's office has issued the following statement, which I fully endorse:

Take care of yourself. Do your best to maintain a healthy lifestyle this semester by eating well, exercising, avoiding drugs and alcohol, getting enough sleep and taking some time to relax. This will help you achieve your goals and cope with stress.

All of us benefit from support during times of struggle. You are not alone. There are many helpful resources available on campus and an important part of the college experience is learning how to ask for help. Asking for support sooner rather than later is often helpful.

If you or anyone you know experiences any academic stress, difficult life events, or feelings like anxiety or depression, we strongly encourage you to seek support. Counseling and Psychological Services (CaPS) is here to help: call 412-268-2922 and visit their website at `http://www.cmu.edu/counseling`. Consider reaching out to a friend, faculty or family member you trust for help getting connected to the support that can help.

If you or someone you know is feeling suicidal or in danger of self-harm, call someone immediately, day or night:

- CaPS: 412-268-2922
- resolve Crisis Network: 888-796-8226

If the situation is life threatening, call the police:

- On campus: CMU Police: 412-268-2323

- Off campus: 911

If you have questions about this or about your coursework, please let me know.

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Academic integrity

Although it is unfortunate in a university like Carnegie Mellon, I find it necessary to call your attention to the various university policies on academic integrity.

Please understand that we take any form of cheating or plagiarism very seriously. As a scientist or engineer your reputation is of supreme importance. It is simply not worth sacrificing the integrity with which you are known for something as trivial and transitory as a homework or exam grade on a course. And in the end, your throrough mastery of the course material, which you can only attain by doing your own work, will be far more valuable to you than the grade you receive for this course.

In this course it is considered acceptable (and even desirable) for students to discuss the general approach to be taken for homework problems and lab projects with each other. Nevertheless, work handed in for grading must be a product of your own individual effort, so solutions which are nearly exact copies of one another are evidence of an unacceptable collaboration. Looking up solutions to problems on the Web is not permitted under any circumstances, nor is using any information from exams and homework sets from previous years in this course. Finally, all work turned in on exams must represent your efforts alone.

This year for the first time we are becoming concerned about the potential utility of the use of generative AI tools (such as ChatGPT and its competitors) for providing inappropriate assistance in completing the homework assignments, including especially the homework problems. For the time being, the use of generative AI tools in completing your homework assignments is strictly prohibited. It is understood that the creative use of these technologies can be useful in this course, and suggestions from anyone on how to better combine generative AI tools in this course are appreciated, and the strict prohibition against AI tools may be modified if circumstances warrant such a change.

The ECE Academic Integrity Policy

`http://www.ece.cmu.edu/programs-admissions/masters/academic-integrity.html`

The Department of Electrical and Computer Engineering adheres to the academic integrity policies set forth by Carnegie Mellon University and by the College of Engineering. ECE students should review fully and carefully Carnegie Mellon University's policies regarding Cheating and Plagiarism; Undergraduate Academic Discipline; and Graduate Academic Discipline. ECE graduate student should further review the Penalties for Graduate Student Academic Integrity Violations in CIT outlined in the CIT Policy on Graduate Student Academic Integrity Violations. In addition to the above university and college-level policies, it is ECE's policy that an ECE graduate student may not drop a course in which a disciplinary action is assessed or pending without the course

instructor's explicit approval. Further, an ECE course instructor may set his/her own course-specific academic integrity policies that do not conflict with university and college-level policies; course-specific policies should be made available to the students in writing in the first week of class.

This policy applies, in all respects, to this course.

The CMU Academic Integrity Policy

`http://www.cmu.edu/academic-integrity/index.html`

In the midst of self exploration, the high demands of a challenging academic environment can create situations where some students have difficulty exercising good judgment. Academic challenges can provide many opportunities for high standards to evolve if students actively reflect on these challenges and if the community supports discussions to aid in this process. It is the responsibility of the entire community to establish and maintain the integrity of our university.

This site is offered as a comprehensive and accessible resource compiling and organizing the multitude of information pertaining to academic integrity that is available from across the university. These pages include practical information concerning policies, protocols and best practices as well as articulations of the institutional values from which the policies and protocols grew. The Carnegie Mellon Code, while not formally an honor code, serves as the foundation of these values and frames the expectations of our community with regard to personal integrity.

This policy applies, in all respects, to this course.

The Carnegie Mellon Code

Students at Carnegie Mellon, because they are members of an academic community dedicated to the achievement of excellence, are expected to meet the highest standards of personal, ethical and moral conduct possible. These standards require personal integrity, a commitment to honesty without compromise, as well as truth without equivocation and a willingness to place the good of the community above the good of the self. Obligations once undertaken must be met, commitments kept.

As members of the Carnegie Mellon community, individuals are expected to uphold the standards of the community in addition to holding others accountable for said standards. It is rare that the life of a student in an academic community can be so private that it will not affect the community as a whole or that the above standards do not apply.

The discovery, advancement and communication of knowledge are not possible without a commitment to these standards. Creativity cannot exist without acknowledgment of the creativity of others. New knowledge cannot be developed without credit for prior knowledge. Without the ability to trust that these principles will be observed, an academic community cannot exist.

The commitment of its faculty, staff and students to these standards contributes to the high respect in which the Carnegie Mellon degree is held. Students must not destroy that respect by their failure

to meet these standards. Students who cannot meet them should voluntarily withdraw from the university.

This policy applies, in all respects, to this course.

Carnegie Mellon University's Policy on Cheating

`http://www.cmu.edu/academic-integrity/cheating/index.html`

According to the University Policy on Academic Integrity, cheating "occurs when a student avails her/himself of an unfair or disallowed advantage which includes but is not limited to:

- Theft of or unauthorized access to an exam, answer key or other graded work from previous course offerings.
- Use of an alternate, stand-in or proxy during an examination.
- Copying from the examination or work of another person or source.
- Submission or use of falsified data.
- Using false statements to obtain additional time or other accommodation.
- Falsification of academic credentials."

This policy applies, in all respects, to this course.

Carnegie Mellon University's Policy on Plagiarism

http://www.cmu.edu/academic-integrity/plagiarism/index.html According to the University Policy on Academic Integrity, plagiarism "is defined as the use of work or concepts contributed by other individuals without proper attribution or citation. Unique ideas or materials taken from another source for either written or oral use must be fully acknowledged in academic work to be graded. Examples of sources expected to be referenced include but are not limited to:

- Text, either written or spoken, quoted directly or paraphrased.
- Graphic elements.
- Passages of music, existing either as sound or as notation.
- Mathematical proofs.
- Scientific data.
- Concepts or material derived from the work, published or unpublished, of another person."

This policy applies, in all respects, to this course.

Carnegie Mellon University's Policy on Unauthorized Assistance

`http://www.cmu.edu/academic-integrity/collaboration/index.html`

According to the University Policy on Academic Integrity, unauthorized assistance "refers to the use of sources of support that have not been specifically authorized in this policy statement or by the course instructor(s) in the completion of academic work to be graded. Such sources of support may include but are not limited to advice or help provided by another individual, published or unpublished written sources, and electronic sources. Examples of unauthorized assistance include but are not limited to:

- Collaboration on any assignment beyond the standards authorized by this policy statement and the course instructor(s).
- Submission of work completed or edited in whole or in part by another person.
- Supplying or communicating unauthorized information or materials, including graded work and answer keys from previous course offerings, in any way to another student.
- Use of unauthorized information or materials, including graded work and answer keys from previous course offerings.
- Use of unauthorized devices.
- Submission for credit of previously completed graded work in a second course without first obtaining permission from the instructor(s) of the second course. In the case of concurrent courses, permission to submit the same work for credit in two courses must be obtained from the instructors of both courses."

This policy applies, in all respects, to this course.

Carnegie Mellon University's Policy on Research Misconduct

`http://www.cmu.edu/academic-integrity/research/index.html`

According to the University Policy For Handling Alleged Misconduct In Research, "Carnegie Mellon University is responsible for the integrity of research conducted at the university. As a community of scholars, in which truth and integrity are fundamental, the university must establish procedures for the investigation of allegations of misconduct of research with due care to protect the rights of those accused, those making the allegations, and the university. Furthermore, federal regulations require the university to have explicit procedures for addressing incidents in which there are allegations of misconduct in research."

The policy goes on to note that "misconduct means:

- fabrication, falsification, plagiarism, or other serious deviation from accepted practices in proposing, carrying out, or reporting results from research;
- material failure to comply with Federal requirements for the protection of researchers, human subjects, or the public or for ensuring the welfare of laboratory animals; or
- failure to meet other material legal requirements governing research."

"To be deemed misconduct for the purposes of this policy, a 'material failure to comply with Federal requirements' or a failure to meet other material legal requirements' must be intentional or grossly negligent."

To become familiar with the expectations around the responsible conduct of research, please review the guidelines for Research Ethics published by the Office of Research Integrity and Compliance.

This policy applies, in all respects, to this course.

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Topic Outline for 2024

Multirate Digital Signal Processing

- Review of continuous-time sampling
- Sampling rate conversion
- Efficient change of sample rate: general and polyphase implementations
- Multistage implementations, with applications to speech and music analysis

Short Time Fourier Analysis

- General introduction
- Fourier transform, lowpass and bandpass implementations
- Phase vocoding
- Application to speech and music analysis

Stochastic Processes

- Review of probability theory
- Basic properties of random processes: stationarity and ergodicity
- Autocorrelation and covariance functions
- Random processes and linear filters
- Power spectral density functions

Classical and Modern Spectral Analysis

- Traditional approaches using the periodogram
- Smoothed periodograms
- Nonlinear estimation: the maximum entropy method
- Applications to signal analysis and linear prediction

Linear Prediction

- Autocorrelation and covariance implementations

- Design and interpretation of lattice filters
- Applications to speech, bioinformation processing, and geophysics

Adaptive Filtering

- General introduction and overview
- Adaptive FIR filters: the MMSE, LMS, and RLS algorithms
- Lattice filters: filter derivation and design
- Adaptive array processing and beamforming

Additional topics (not all will be covered)

- Homomorphic signal processing and the complex cepstrum
- Generalized time-frequency representations: Wigner distributions and wavelets

TENTATIVE COURSE OUTLINE

Note: This information is provided only to give you a rough idea of how the course material will be presented, and most likely presents an overly optimistic timetable. In addition, the curriculum is changing somewhat during this year, which will impose some additional variations. Hence, all specific details are subject to change. Sections are specified in terms of sections of the class notes.

Date	Lecture topic (Section numbers in the class notes)
8/26	Course introduction
8/28	Review of continuous-time sampling (1.1 - 1.3)
9/2	**LABOR DAY (no class)**
9/4	Change in sampling rate (1.4)
9/9	Efficient structures for decimation and interpolation (2.1 - 2.2)
9/11	Mathematical characterization of interpolation and change of sampling rate (2.2 - 2.3)
9/16	Introduction to short-time Fourier analysis (3.1 - 3.4)
9/18	Short-time Fourier synthesis (3.5 - 3.6)
9/23	STFT applications and phase vocoding (3.7
9/25	Intro to stochastic processes (4.1 - 4.3)
9/30	Ergodicity, Gaussian RPs, Power spectral density functions (4.3 - 4.5)
10/2	PSD functions, RPs through LSI systems, Intro to parameter estimation (4.5 - 5.2)
10/7	Performance of simple estimators (5.2 - 5.4)
10/9	**QUIZ 1**
10/12-20	**FALL BREAK (no classes**
10/21	Estimates of the autocorrelation and PSD functions: the periodogram (5.5 - 5.6)
10/23	Smoothing the periodogram: variance of the periodogram and Bartlett averaging (5.7)
10/28	Spectral estimation by modeling: the Maximum Entropy Method (MEM) for PSD estimation (6.1 -
10/30	Intro to linear prediction (6.4 - 7.2)
11/4	The LPC autocorrelation and covariance methods; computing the LPC gain (7.2)
11/6	Lattice filters and the PARCOR method (7.3 - 7.5)
11/11	Introduction to adaptive filtering: the LMS algorithm (8.1 - 8.6
11/13	Performance of adaptive filters: the RLS algorithm (8.6 - 8.7)
11/18	Introduction to narrowband array processing (9.1 - 9.4)
11/20	**QUIZ 2**
12/25	Broadband array processing (9.6)
11/27-29	**THANKSGIVING HOLIDAY (no class)**
12/2	Broadband array processing (9.6)
12/4	Applications of ADSP to robust speech recognition