Digital Signal Processing (18-491/18-691)
Spring Semester, 2023

COURSE SYLLABUS FOR SPRING 2023

Instructor: Professor Richard Stern, PH B26, (412) 916-7386 (cell phone), `rms@ece.cmu.edu`

Course Management Assistant: Course management responsibilities are handled by the ECE Academic Services Center, HH 1113.

Teaching assistants:

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Overview of the course: This course addresses the mathematics, implementation, design and application of the digital signal processing algorithms widely used in areas such as multimedia telecommunications and speech and image processing. Topics include discrete-time signals and systems, discrete-time Fourier transforms and Z-transforms, discrete Fourier transforms and fast Fourier transforms, digital filter design and implementation, and multi-rate signal processing. The course will include introductory discussions of 2-dimensional signal processing, linear prediction, adaptive filtering, and selected application areas. Classroom lectures are supplemented with implementation exercises using MATLAB .

This year we are offering the course in two forms. The course in its traditional form continues to be offered under the number 18-491. In addition, we are offering a second version of the course with the number 18-691, which carries graduate credit. 18-491 and 18-691 will share the same lectures and recitations. Students enrolled in 18-691 will be required to complete some additional work that will be specified shortly.

Grading: Grades for 18-491 will be based in part on performance in three examinations (nominally 67% of the final grade, with the final exam having the weight of 1.5 times the first two exams), and on homework assignments (nominally 33%, with the lowest homework grade dropped from the final grade computation). The weighting of the assignments for 18-691 will be similar, with an additional weight paid to the additional assignments for 18-691.

Prerequisites: 18-290

Undergraduate course designation: area and coverage

Undergraduate course area: Signals & Systems

Class hours: Lectures are Mondays and Wednesdays, 2:00 to 3:50 (Pittsburgh time), in DH 1212. Recitations will meet Fridays from 10:00 to 11:50 in WeH 5310 and from 12:00 to 1:50 in WeH 6423. The major focus of the recitations will be to discuss practical problems, and especially to review useful techniques for completing the following weeks homework. Unofficially, students may attend either recitation session, regardless of which one they are formally enrolled in.

Course textbook: We will again use the Third Edition of the text *Discrete-Time Signal Processing* by A. V. Oppenheim and R. W. Schafer, with M. T. Yoder and W. T. Padgett (Prentice-Hall/Pearson, 2009, ISBN: 978-0131988422, to be referred to as OSYP) as the primary text for the course. This book is the second revision of the original 1989 text by the same name, which in turn is a greatly expanded version of the classic text Digital Signal Processing published in 1975 by the same primary authors. The first two editions of Discrete-Time Signal Processing are more verbose and tutorial than Digital Signal Processing, and they also include some new material that represents developments in signal processing that have taken place since the earlier text was published more than twenty years ago. The Third Edition is a more comprehensive rewrite than before and also includes a companion website with demos. If you wish, you can use one of the earlier editions of *Discrete-Time Signal Processing* (or one of the various International Student Editions), but you will be responsible for mapping the sections of the text that are cited in the problem sets into the corresponding sections in your edition. Students are **STRONGLY** encouraged to obtain a hard copy of the book, either new or used, rather than work from a .pdf file.

Other texts: There is a huge number of good textbooks on the subject of digital signal processing now on the market. *Digital Signal Processing: Principles, Algorithms and Applications* by J. G. Proakis and D. G. Manolakis (Fourth edition, Prentice-Hall/Pearson, 2006) is a text that includes a number of additional topics but that is written in a style that is similar to that of OSYP. There are also several new texts that are integrating MATLAB into the presentation more than OSYP does. One such example is the text *Digital Signal Processing, A Computer-Based Approach* by S. K. Mitra (Third edition, McGraw-Hill, 2005), which has a bit more of an applied flavor than Oppenheim and Schafer.

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 11:59 pm 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.

MATLAB assignments: A component of the homework will be computer assignments using the MATLAB analysis package. You will be given accounts on the educational computers of the ECE department if you need them. 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.

Examinations: The first two exams will be held during the normal class meeting times on March 1 and April 5. The final examination will be scheduled by the Registrar during the final exam period. Please arrange your other commitments so as not to conflict with the announced exam dates. Make-up exams will not be given without extremely compelling reasons.

18-491/18-691 home page and course management platforms: We are maintaining a home page for 18-491/18-691 which may be accessed through the URL

`http://www.ece.cmu.edu/~ece491/`

We will be putting all course handouts, reference documents, and other information on the 18-491/18-691 home page. The pages will also include the MATLAB scripts used for classroom demos and other material presented in the lectures.

We will also make limited use of the Canvas course management platform, primarily for processing and distributing grades, discussing the course material (using Piazza), and turning in homework (using Gradescope).

Office hours: TBA

TOPIC OUTLINE FOR 18-491/18-691

Characterization of DT signals and systems

- Signal representation and convolution
- Discrete-time Fourier transforms and Z-transforms
- Conversion between continuous and discrete time and change of sampling rate

The DFT and the FFT

- Discrete Fourier series, discrete Fourier transforms, and circular convolution
- Fast Fourier transform (FFT) algorithms

Digital filter design and implementation

- FIR and IIR filter structures
- IIR designs from prototype analog filters
- FIR designs using windowing and frequency sampling
- Computer-aided optimal filter design
- Computer-aided optimal filter design

Signal processing in noise

- Introduction to stochastic processes
- Stochastic processes, spectral analysis and LSI systems
- Optimal filtering in noise

Additional topics (not all will be covered)

- Linear prediction
- Lattice filters and their implementation
- Adaptive filters
- Applications to speech and image processing

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 Oppenheim, Schafer, Yoder, and Padgett.

Date	Lecture topic (Section numbers in OYSP)
1/18	Intro to course, review of continuous-time signal and system concepts (1)
1/23	Review of discrete-time signals and systems; convolution (2.0 - 2.4)
1/25	Difference equations and discrete-time Fourier transforms (2.5 - 2.9)
1/30	DTFTs & CTFTs of periodic and sampled signals (4.0 - 4.5)
2/1	Introduction to multi-rate DSP: decimation & interpolation (4.6)
2/6	Implementation of decimation & interpolation; Intro to Z-transforms (4.6-4.7; 3.0- 3.2)
2/8	Z-transform properties and inverses (3.2 - 3.4)
2/13	Z-transforms and frequency response of LSI systems (5.0 - 5.8)
2/15	Intro to discrete Fourier series and the discrete Fourier transform (8.0 - 8.5)
2/20	The DFT and circular convolution (8.5 - 8.7)
2/22	Intro to fast Fourier transform algorithms (9.0, 9.2)
2/27	FFT structures, algorithms, and computational considerations (9.3 - 9.5)
3/1	**QUIZ 1**
3/4-11	**SPRING BREAK (no classes)**
3/13	Intro to digital filter implementation 96.3 - 6.4)
3/15	IIR filter structures and implementation (6.3 - 6.4)
3/15	FIR structures and implementation (6.5)
3/22	IIR filter design based on analog prototypes (7.0 - 7.3)
3/27	FIR design using windows (7.5-7.6)
3/29	Computer-aided FIR design: The Parks-McClellan algorithm (7.7-7.8)
4/3	Characterizing random signals and noise (Appendix A)
4/5	**QUIZ 2**
4/10	Intro to linear prediction (11.1-11.6)
4/12	Linear prediction and lattice filters (11.7)
4/13-15	**SPRING CARNIVAL (no class)**
4/17	Intro to adaptive filters (notes)
4/19	Intro to two-dimensional signal processing (notes)
4/24	Short-time Fourier analysis and spectrograms (10.0 - 10.5)
4/26	Final review
5/1-9	**Final exam period**

Relationship of educational objectives of 18-491/18-691 to ABET program outcomes

(a) **an ability to apply knowledge of mathematics, science, and engineering:** students learn how to extend the fundamental mathematics of linear systems analysis to the application of digital filter design and implementation, high-speed convolution, multi-rate signal processing, linear prediction, and assorted applications.

(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:** design and implementation alternatives from practical specifications for digital signal processing are discussed in terms of tradeoffs between computational cost, memory requirements, and system performance.

(e) **an ability to identify, formulate, and solve engineering problems:** mathematical tools are used to formulate solutions to design problems in filtering, spectral analysis, and other application areas.

(i) **a recognition of the need for, and an ability to engage in life-long:** the techniques developed for this course are placed in the context of the fundamental principles from which they are derived as well as the techniques needed for more advanced work in the field. Continued education as well as participation in the professional literature is always encouraged.

(j) **a knowledge of contemporary issues:** the course work is discussed in terms of contemporary signal processing problems and their solutions.

(k) **an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice:** students use industry-standard computational tools, with a focus on MATLAB , throughout the course in homework assignments to implement the procedures that are presented in class. Students complete the course with a thorough exposure to the MATLAB procedures that are most relevant to the topics discussed.

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 and others over the years has highlighted the extent to which endemic bias and discrimination can and do have lethal consequences. And this has been reflected by violence directed toward individuals of Asian descent in more recent years as well as ongoing antipathy toward some worshippers of Islam. 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 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.

For several years the ECE Diversity, Inclusion, and Outreach Committee has worked 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.

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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