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Music 320 A & B: Introduction to Digital Audio Signal Processing

1 Course Description

Music 320 is a two-quarter first-course in digital signal processing with applications in computer music and audio.

The lectures present fundamental elements of digital audio signal processing, such as sinusoids, spectra, the Discrete Fourier Transform (DFT), digital filters, z transforms, transfer-function analysis, and basic Fourier analysis in the discrete-time case. Matlab is used for in-class demonstrations and homework/lab assignments. The labs focus on practical applications of the theory, with emphasis on working with waveforms and spectra, "getting sound", and developing proficiency in the matlab language.

Prerequisites: High-school level algebra and trigonometry, some calculus, and prior exposure to complex numbers.

Time and Place

Term: Autumn and Winter Quarters
Location: CCRMA Classroom (Knoll 217)
Lectures: Tuesdays and Thursdays 3:00–4:50 PM
Units: 3–4
Instructor: Julius O. Smith (jos@ccrma.stanford.edu)
TA: Iran Roman (iran@ccrma.stanford.edu)
Office Hours: See “Office Hours and Getting Help” below
Schedule: See “Schedule and Pointers” below

2 Administrative Information

2.1 Announcements

Class announcements are often made via email. For this we are presently using Piazza:

[https://piazza.com/stanford/fall2016/music320a/home](https://piazza.com/stanford/fall2016/music320a/home)

You should have received an invitation from Piazza to join the class after you signed up for it in axess (using the email address known to axess). Otherwise, please join by visiting the above URL and entering your preferred email address.

2.2 Assignments

There are five homework/lab assignments, each covering roughly two weeks of the course. In each two-week “section”, the first week is devoted primarily to theory while the second week is focused more on software and applications. Thus, each assignment contains both a theory and laboratory part. The lab portion typically requires programming in matlab.

Each assignment is typically announced on Tuesday in the first week of the section. The theory part is normally due the following Tuesday at 3:15 pm in the 320 mailbox (located in the Knoll, central wing, second floor, facing the printer). The lab part is normally due by midnight the following Friday, i.e., at the end of the two-week section.

For lab assignments, we will be using the Canvas website. To sign up, go to the Canvas website and find Music320A. Once you are enrolled in the class, you can upload your matlab files in the “drop box” on the left menu.

See §2.5 below regarding obtaining help with theory and lab assignments.

Regarding late homeworks, 7 free late days are allowed (with hours rounded up to the nearest day). Late homeworks beyond this will not be accepted. Only up to 3 late days can be used for any one assignment. When using late days, students are required to write the number of late days used at the top of the assignment (date and time).

Students are encouraged to discuss the homework assignments with each other. It is fine to learn from a classmate how to solve any of the homework problems, but each student is responsible for carrying out and writing up the assignments individually. It is an honor code violation to copy the work of others.

2.3 Exams

The final examination will be held in the CCRMA Classroom (Knoll 217) on the University-assigned date, also listed for convenience in the class schedule (§6 on page 4).

2.4 Grading

Grades are based on the homeworks/labs (60%), and the final exam (40%). There are also bonus points available based on general participation. The weightings may be changed as we see fit.

2.5 Office Hours and Getting Help

We will be using Piazza for sharing answers to posted questions with the whole class. To sign up, see the 320 Piazza site. It is free and allows you to view past questions from other students, and discuss questions together. Try it first for any homework questions you may have. You are also welcome, of course, to catch us whenever you see us at CCRMA, such as during office hours, etc.

TA weekly office hours will be announced in class and via email to the class. Meetings with JOS are arranged via email for half-hour slots after class, or other times when necessary.

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*https://canvas.stanford.edu*
*https://www.piazza.com*
*https://piazza.com/stanford/fall2016/music320a/home*
2.6 Computer Usage

Lab exercises will be computer based. All students may obtain a computer account at CCRMA in order to use the computer facilities. It is also possible to work entirely on your own computer, as long as you have the necessary software. However, note that some course materials are restricted to on-campus access, so you should have at least one Stanford computer account from which you access those.

Here is how to obtain a CCRMA computer account:

https://cm-knoll.stanford.edu/usersignup

Note: This link only works at CCRMA.

Once you have your account, please log in at CCRMA and take a look at the User’s guide tab in the left-frame menu of the main CCRMA website to learn more about computer usage and other facilities at CCRMA.

3 Textbooks

Music 320A (fall) is based on assigned chapters of

Mathematics of the Discrete Fourier Transform (DFT) by Julius O. Smith

Music 320B (winter) is based on assigned chapters of

Introduction to Digital Filters by Julius O. Smith

See § for the list of assigned chapters. Both books are fully available on-line. Softcover versions are available from Amazon.com.

4 The Partially Flipped Classroom

With the lectures recorded, class time is freed up for other activities. Here is how a typical “partially flipped class” is organized:

• Q&A session on the reading/video content
• Review of main points in the reading/videos
• Demos in support of the reading/videos
• Presentation of the homework/lab assignment
• Worked problems similar to those in the homework
• Matlab session on theory/lab-related topics
• Live coding in matlab

Additional available time may be devoted to:

• More demos
• More discussion

http://ccrma.stanford.edu/guides/
http://ccrma.stanford.edu/~jos/mdft/
http://ccrma.stanford.edu/~jos/filters/
• “Backwards learning” examples:
  • Plugins using spectral techniques
  • Faust language and some of its examples
• More on applications and why all this is useful
• Preview material coming up
• General in-class discussion
• Getting to know your fellow class-members better

5 A Recipe for Learning

Learning something new requires multiple passes on the material. For example:

1. Do the assigned reading at a fixed pace to get a picture of what’s covered
2. Watch the lecture videos, pausing and taking notes on anything newly learned
3. Make a first pass on the homework, flagging and skipping when stuck on a problem
4. Discuss nonobvious homework problems with other students, the TA, and/or JOS
5. Write up the homework problems, everything now understood
6. Exam prep: Reread the text for full comprehension
7. Exam prep: Reread your notes
8. Prepare your one-page summary of the course allowed in the exam
9. Exam experience: Exercise in problem solving using the material

These multiple engagements typically result in a fair amount of learning.

6 320B Schedule and Pointers

6.1 Section 3: Digital Filter Design

• Reading:
  - Chapter 10 (Elementary Audio Digital Filters)
  - Chapter 11 (Filters Preserving Phase)
  - Appendix I (Recursive Digital Filter Design)
  - Appendix I.2 (Butterworth Filters)
  - Appendix K (Digital Filtering in FAUST and Pd)
    Supplementary: Audio Signal Processing in FAUST

• Assignment 2

• Lecture Videos (Total Viewing Time ≈ 2 Hours):
Analog Filters Reviewed: Transfer Function, Frequency Response, Power Response; Analog Lowpass Design, Maximally Flat Passband, Butterworth Filters\footnote{https://www.youtube.com/watch?v=doDMm2EfEbg}\footnote{30:46}

Butterworth Filter Properties: Maximum Flatness at Infinity, Low Ringing, Mild Phase Response, Poles on a Circle; Spectral Factorization, Series Biquad Realization, Elliptic Function Filters, Chebyshev Optimality, Remez Exchange (Parks-McLellan), firpm in matlab, cvx for Convex Optimization\footnote{https://www.youtube.com/watch?v=pUtUrzVHF3Q}\footnote{35:19}

Supplementary: Introduction to Functional Audio Stream (FAUST): Simplest Lowpass, Utilities in Faust’s filter.lib\footnote{https://www.youtube.com/watch?v=FEf7dpApd6I}\footnote{37:30}

Supplementary: More FAUST: Testing filters using faust2octave\footnote{https://www.youtube.com/watch?v=Ao1ZriZi8nY}\footnote{27:32}

Butterworth Power Response, Analytic Continuation, Butterworth Poles, Matlab butter() Function\footnote{https://www.youtube.com/watch?v=nhhuAxBUl6U}\footnote{7:02}

Example Butterworth Filter of Order 2, Digitization via Bilinear Transform, Frequency Prewarping\footnote{https://www.youtube.com/watch?v=UcTHnf4B5tU}\footnote{18:49}

Digital Filter Design and Implementation in Matlab: Noise Removal via Lowpass Filtering, Create Sinusoid and Noise, Matlab’s butter(), filter(), fdatool (Filter Design and Analysis tool), Simulating a Telephone Channel Bandwidth\footnote{https://www.youtube.com/watch?v=I0g5r0_BgRM}\footnote{10:30}

Matlab: freqz(), freqs(); Continuous Butterworth Filter Analysis; Converting to Second-Order Sections in Matlab using tf2sos(); Viewing Butterworth Poles in Matlab using zplane(); Excess Delay at Filter Cutoff; grpdelay(); Elliptic Filters using ellip(); Ripple; impz(); Zero Phase versus Minimum Phase (Pre-Ring versus Post-Ring); Minimum-Delay Property of Minimum-Phase Filters; Partial Fraction Expansion in Matlab using residue(), residuez(), or residued()\footnote{https://www.youtube.com/watch?v=MxxDS01Ea5o}\footnote{31:10}

6.2 Section 4: Quality Factor Q, Allpass Filters, State Space, State Variable Filter

- Reading:
  - Appendix E.7 (Quality Factor (Q))
  - Appendix C (Allpass Filters)
  - Laplace Analysis of a Force-Driven Mass
  - State-Space Formulation of Digital Filters
  - State-Variable Filter
  - Supplementary: State-Space Introduction in Music 420
  - Supplementary: State-Space Canonical Forms
– Supplementary:
  Linkwitz-Riley Crossovers: A Primer
  Linkwitz-Riley filter
– Assignment 8

• Lecture Videos (Total Viewing Time ≈ 3 Hours):
  – Quality Factor (Q) of a Resonator\(^{17}\) [7:12]
  – Complex One-Pole Resonator and its Q; Canonical Form of a Biquad (s-plane); Mechanical and Electrical Resonators; Limiters, Compressors, Expanders\(^{18}\) [39:30]
  – Filter Decay Time is about Q Periods\(^{19}\) [3:16]
  – Bilinear Transform Frequency Mapping, Analog Computers, State Space Formulation, Physical Derivation of Bilinear Transform, State Variable\(^{20}\) [38:29]
  – Minimum Phase Filters and Signals; Allpass Filters: Poles and Zeros, Graphical Amplitude and Phase Response, Biquad Realization, Phasing; Allpass-Minimum-Phase Decomposition\(^{21}\) [28:44]
  – Allpass Filters in z and s Planes; Instability as Noncausality; Laurent Series; Bilateral DTFT; Cepstrum; Converting Arbitrary Spectra to Minimum-Phase Form\(^{22}\) [39:13]
  – Repeated Poles at \(s = 0\)
    * One Pole at DC in the s Plane\(^{23}\) [14:17]
    * Mechanical Integrator using a Mass\(^{24}\) [3:46]
    * Integrator made by a Spring or Inductor\(^{25}\) [5:46]
    * One Pole at DC in the s Plane, Continued\(^{26}\) [1:31]
    * Frequency Response of an Integrator\(^{27}\) [5:05]
    * Repeated Poles at DC\(^{28}\) [4:16]
    * General Transfer Function of a Pile of Poles at DC\(^{29}\) [3:38]
    * Impulse Response of a Pile of Poles at DC\(^{30}\) [3:22]
  – The State Space Formulation of Linear Systems [2016 flipped-class review]
    * Adding Feedback around the Integrator Chain, Derivation of the State Space Formulation\(^{31}\) [10:46]
6.3 Section 5: Voice Synthesis, F0 Estimation, Cepstra, Converting to Minimum Phase

- Reading:
  - Chapter 12 (Minimum Phase Digital Filters)
– **Supplementary:** Spectral Envelopes via Cepstrum or LPC [from Music 421 overheads]

**Lecture Videos:**

– Minimum-Phase Spectra Play-List
– Complex and Real Cepstrum, Quefrency [7:54]
– Mel Frequency Cepstral Coefficients (MFCC); Bark and Equivalent Rectangular Bandwidth (ERB) Psychoacoustic Frequency Scales based on Critical Bands of hearing [7:54]
– Complex Cepstrum Derived; Converting Mixed-Phase Signals to Minimum Phase [5:39]
– Series Expansion of Log of 1/(1-x) [7:57]
– Series Expansion of Log Transfer Function in Factored Form [5:26]
– Contribution of Zeros to the Complex Cepstrum [3:15]
– Contribution of Poles and Zeros (Inside and Outside the Unit Circle) to the Complex Cepstrum; Nonparametric Cepstral Folding Method for Converting Mixed Phase to Minimum Phase using the FFT; Testing for Time Aliasing [9:14]
– Nonparametric Cepstral Folding Method in Matlab: minphasespec(), fold(), invfreqz() [6:11]
– Review of another Cepstral Folding Example [19:08]
– Minimum Phase Conversion by Spectral Factorization or Cepstral Method [5:45]
– Minimum Phase Conversion by the Cepstral Method, Continued [12:10]
– Cepstral Method Code, then CollideFX Demo by Chet Gnegy [55:51]
– Supplementary: Voice Vowel Synthesis in Faust, Continued []
– Supplementary: Voder [0:43]
– Supplementary: Phonem for iPad by Wolfgang Palm

[50] https://www.youtube.com/watch?v=Tlk6CLc1PPU
[51] https://www.youtube.com/watch?v=201BBFeQCGE
[52] https://www.youtube.com/watch?v=OHiz4GW-7UA
[53] https://www.youtube.com/watch?v=wrs1b9U7HaI
[54] https://www.youtube.com/watch?v=x3gCA_rj13k
[55] https://www.youtube.com/watch?v=ni1Y8EA4-peA
[56] https://www.youtube.com/watch?v=--yA0lV橐o
[57] https://www.youtube.com/watch?v=PTx0capBmHU
[58] https://www.youtube.com/watch?v=V7K4rmT94PE
[59] https://www.youtube.com/watch?v=7GccXcMcqVao
[60] https://www.youtube.com/watch?v=6RNeaaFxFvG
[61] https://www.youtube.com/watch?v=nkt3bRU4tI4
[62] https://www.youtube.com/watch?v=GR97SMvQ4Pw
[63] https://www.youtube.com/watch?v=e5gQBei-z-c
[64] https://www.youtube.com/watch?v=GR97SMvQ4Pw