

# MUS320A&B: Introduction to Digital Audio Signal Processing

Center for Computer Research in Music and Acoustics (CCRMA)  
Department of Music, Stanford University

320A (spectra): Autumn Quarter

320B (filters): Winter Quarter

2017–2018

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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:** 2–4

**Instructor:** Julius O. Smith ([jos@ccrma.stanford.edu](mailto:jos@ccrma.stanford.edu))

**TA:** Rahul Agnihotri ([ragni@ccrma.stanford.edu](mailto:ragni@ccrma.stanford.edu))

**Office Hours:** See "Office Hours and Getting Help"<sup>1</sup> below

**Schedule:** See "Schedule and Pointers"<sup>2</sup> 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/winter2018/music320b/home>

If you signed up for the class in axess before the first day of classes, you should receive an invitation from Piazza to join the class (using the email address known to axess). Otherwise, please join by visiting the above URL and entering your preferred email address.

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<sup>1</sup>[http://ccrma.stanford.edu/~jos/intro320/Office\\_Hours\\_Getting\\_Help.html](http://ccrma.stanford.edu/~jos/intro320/Office_Hours_Getting_Help.html)

<sup>2</sup><http://ccrma.stanford.edu/~jos/intro320/>

## 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 Thursday during the first week of the section. The theory part is normally due the following Thursday at class time, 3 pm, in the 320 mailbox at CCRMA. The lab part is normally due by midnight the following day, i.e., at the end of the two-week section. Available homework time after turning in the assignments should be devoted to viewing the lecture videos for the next section.

For lab assignments, we will be using the Canvas<sup>3</sup> website. To sign up, go to the Canvas website and find Music320B. 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 be penalized at 5% per day. When using late days, 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<sup>4</sup> for sharing answers to posted questions with the whole class. To sign up, see the 320 Piazza site.<sup>5</sup> 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 are Wednesday evenings 7:30-9:30 PM in the CCRMA Ballroom (2nd floor). Meetings with JOS are arranged via email for half-hour slots after class, or other times when necessary.

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<sup>3</sup><https://canvas.stanford.edu>

<sup>4</sup><https://www.piazza.com>

<sup>5</sup><https://piazza.com/stanford/winter2018/music320b/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 guides<sup>6</sup> 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)**,<sup>7</sup> by Julius O. Smith

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

**Introduction to Digital Filters**,<sup>8</sup> by Julius O. Smith

See §6 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

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<sup>6</sup><http://ccrma.stanford.edu/guides/>

<sup>7</sup><http://ccrma.stanford.edu/~jos/mdft/>

<sup>8</sup><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 result in a good amount of learning.

## 6 Schedule and Pointers

**Note:** The online version<sup>9</sup> of this schedule contains hyperlinks to all reading, lecture videos, and assignments.

To obtain printable versions of the assignments and solutions from off-campus locations, you can use commands such as

```
scp you@ccrma-gate.stanford.edu:/usr/ccrma/web/html/courses/320/hw/hw1x/hw1x.pdf .
scp you@ccrma-gate.stanford.edu:/usr/ccrma/web/html/courses/320/hw/hw1x/hw1xsol.pdf .
```

where `you` refers to your CCRMA login, and `x` is `a` for 320A and `b` for 320B.

You can alternatively use VPN<sup>10</sup> (Virtual Private Network) access.

For more info, see <https://ccrma.stanford.edu/guides/remotearchive/>.

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<sup>9</sup>[https://ccrma.stanford.edu/~jos/intro320/Lectures\\_Assignments.html](https://ccrma.stanford.edu/~jos/intro320/Lectures_Assignments.html)

<sup>10</sup><https://uit.stanford.edu/service/vpn>

# Music 320B

## 6.1 Section 1: Linearity and Time Invariance; Time-Domain Representations

- **Reading:**

- Chapters 1 and 2 of **Introduction to Digital Filters**<sup>11</sup>
- Chapter 4 (Linearity and Time Invariance) and Chapter 5 (Time Domain Filter Representations) of **Introduction to Digital Filters**
- First section of Chapter 9 (Implementation Structures) on the Four Direct Forms
- Optionally peruse the Music 421 overheads pertaining to acyclic convolution
- Supplementary: Audio Signal Processing in FAUST
- Assignment 1

- **Lecture Videos (Total Viewing Time  $\approx$  2 Hours):**

**IMPORTANT NOTICE:** The videos are hosted on YouTube and they use *annotations* for corrections and supplementary information. These annotations are *not supported on mobile devices*. It is therefore unfortunately important to view these videos *in a Web browser on a desktop/laptop computer*.

- Linear Time-Invariant (LTI) Filters, Convolution, Linearity, Nonlinear Example, Time-Varying Example, Ideal Lowpass Filter, Pass Band, Cutoff Frequency, Guard Band, Stop Band, Transition Band, Simplest Lowpass Filter, Impulse Response, DTFT, Frequency Response, Amplitude Response, Phase Response, Linear Phase, Sinewave Analysis<sup>12</sup> [38:36]
- Derivation of Convolution from Linearity and Time-Invariance (LTI) (Superposition) [2015]<sup>13</sup> [29:08]
- Recursive Filters, Simplest Lowpass, Phase Delay, Group Delay<sup>14</sup> [28:01]
- Supplementary: FAUST in the Classroom<sup>15</sup> [41:00]
- Supplementary: FAUST Intro<sup>16</sup> [26:00]
- Supplementary: FAUST Implementation of the Simplest Lowpass Filter<sup>17</sup> [18:22]
- Simplest RECURSIVE LPF, Pole Gain, PFE, Time-Constant of a Pole, Stability Pole, Bandwidth, Laplace Transform, s-plane poles and zeros, s-plane pole corresponds to exponential<sup>18</sup> [38:37]

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<sup>11</sup><https://ccrma.stanford.edu/~jos/filters/filters.html>

<sup>12</sup><https://www.youtube.com/watch?v=p19QzBxnhvg>

<sup>13</sup><https://www.youtube.com/watch?v=KWhqV95fKRw>

<sup>14</sup><https://www.youtube.com/watch?v=rOfg8eZAKGs>

<sup>15</sup><https://www.youtube.com/watch?v=21Et7dszi00>

<sup>16</sup>[https://www.youtube.com/watch?v=qE1\\_UzQZnnM](https://www.youtube.com/watch?v=qE1_UzQZnnM)

<sup>17</sup><https://www.youtube.com/watch?v=jNcKGlMHE9A>

<sup>18</sup><https://www.youtube.com/watch?v=iJ7mnqhVBfk>

- Direct Form Digital Filters, Transposing a Flow Graph, Transposed Direct Forms 1 and 2, Direct Form 1 Biquad, Direct Form 2 Biquad, Transposed Direct Form 2 Biquad, Interpolated Delay-Line Read, Interpolated Delay-Line Write = Transpose of Read<sup>19</sup> [14:35]
- Simplest Mechanical LPF: Ideal Mass on Frictionless Surface, Newton’s law of motion  $f=ma$ , Analog Transfer Function for Driving-Force Input, Velocity Output, Admittance (Mobility) of a Mass<sup>20</sup> [5:31]
- Simplest Mechanical LPF: Ideal Mass on Frictionless Surface, Differentiation Theorem for Laplace Transforms, Transfer Function of the Force-Driven Mass: Frequency Response, Poles and Zeros,, Amplitude Response, 6dB per octave roll off, Bode Plot, Harald Bode, Phase Response<sup>21</sup> [27:29]

## 6.2 Section 2: Analysis of Digital Filters

- **Reading:**

- Chapter 6 (Z-transform),
- Chapter 6 (Transfer Function Analysis)
- Chapter 7 (Frequency Response Analysis)
- First three sections of Chapter 8 (Pole-Zero Analysis)
- Appendix D (Laplace Transform Analysis)
- Appendix E (Analog Filters)
- Appendix I.3 (Bilinear Transform)
- Supplementary: Interactive Möbius Transformation

- Assignment 2

- **Lecture Videos (Total Viewing Time  $\approx$  2 Hours):**

- Z Transform, Poles and Zeros, Graphical Amplitude and Phase Response, Phase Delay, Group Delay<sup>22</sup> [27:49]
- Simplest Electrical LPF: RC lowpass; RLC Circuits: Resistor Equation  $V = IR$ , Capacitor Equation  $Q = CV$ , Inductor Equation  $V = L \, di/dt$ ; Kirchhoff Node and Loop Analysis: Kirchhoff Loop Constraint (Sum of voltages around a loop is zero), Kirchhoff Node Constraint (Sum of currents into a node is zero); Voltage Transfer Circuits, Laplace Transform Circuit Analysis, Transfer Function of RC LPF: Pole-Zero Analysis, Impulse Response, Time Constant of Decay, Bode Plot<sup>23</sup> [21:39]
- Simplest Electrical LPF: RC lowpass, continued; Bode Plot; 3dB Bandwidth<sup>24</sup> [7:45]

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<sup>19</sup><https://www.youtube.com/watch?v=qZUcTsHkHBQ>

<sup>20</sup>[https://www.youtube.com/watch?v=BULkMAst6\\_U](https://www.youtube.com/watch?v=BULkMAst6_U)

<sup>21</sup><https://www.youtube.com/watch?v=YWJPqHhjf8c>

<sup>22</sup><https://www.youtube.com/watch?v=hze4CwetVNA>

<sup>23</sup><https://www.youtube.com/watch?v=dEmmtsN-ka4>

<sup>24</sup><https://www.youtube.com/watch?v=MOBH66RyXZw>

- Bandwidth of a Pole, Continuous-Time Complex Resonator and Allpass Filter<sup>25</sup> [22:16]
- Bilinear Transform = special case of Moebius Transformation [DON'T MISS THIS ONE!]<sup>26</sup> [2:34]
- Bilinear Transform Frequency Scaling, Resonance Preservation; Digitizing an Integrator (Mass), RC Filter, Low Shelf; BLT Stability Preservation<sup>27</sup> [8:51]

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<sup>25</sup><https://www.youtube.com/watch?v=m4zCmVVKFso>

<sup>26</sup><https://www.youtube.com/watch?v=JX3VmDgiFnY>

<sup>27</sup><https://www.youtube.com/watch?v=aaGdgf65PsY>