

# 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

2020–2021

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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:** Mondays and Wednesdays 2:30–3:50 PM

**Units:** 3

**Instructors:** Aut (320A): Marina Bosi (mab@ccrma.stanford.edu)  
Win (320B): Jonathan Abel (abel@ccrma.stanford.edu)  
and Dave Berners (dpberner@ccrma.stanford.edu)

**TA:** TBD

**Office Hours:** See "Office Hours and Getting Help"<sup>1</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/fall2020/music320a/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)

## 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>2</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 §2.3 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 Office Hours and Getting Help

We will be using Piazza<sup>3</sup> for sharing answers to posted questions with the whole class. To sign up, see the 320 Piazza site.<sup>4</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.

TA weekly office hours are TBD in the TBD.

## 3 Textbooks

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

**Mathematics of the Discrete Fourier Transform (DFT)**,<sup>5</sup> by Julius O. Smith

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

**Introduction to Digital Filters**,<sup>6</sup> by Julius O. Smith

See §4 for the list of assigned chapters. Both books are fully available on-line. Softcover versions are available from Amazon.com.

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<sup>2</sup><https://canvas.stanford.edu>

<sup>3</sup><https://www.piazza.com>

<sup>4</sup><https://piazza.com/stanford/fall2020/music320a/home>

<sup>5</sup><http://ccrma.stanford.edu/~jos/mdft/>

<sup>6</sup><http://ccrma.stanford.edu/~jos/filters/>

## 4 Schedule and Pointers

**Note:** The online version<sup>7</sup> of this schedule contains hyperlinks to all reading 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>8</sup> (Virtual Private Network) access.

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

## Music 320B

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

- **Demos:**

- Interactive display and hearing of classic *digital filters*<sup>9</sup> by java@falstad.com

- **Reading:**

- Chapters 1 and 2 of **Introduction to Digital Filters**<sup>10</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
- Matrix Filter Representations
- 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>11</sup> [38:36]

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<sup>7</sup>[https://ccrma.stanford.edu/~jos/intro320/Lectures\\_Assignments.html](https://ccrma.stanford.edu/~jos/intro320/Lectures_Assignments.html)

<sup>8</sup><https://uit.stanford.edu/service/vpn>

<sup>9</sup><https://www.falstad.com/dfilter/>

<sup>10</sup><https://ccrma.stanford.edu/~jos/filters/filters.html>

<sup>11</sup><https://www.youtube.com/watch?v=p19QzBxnhvg>

- Derivation of Convolution from Linearity and Time-Invariance (LTI) (Superposition) [2015]<sup>12</sup> [29:08]
- General Linear [Causal] [Time-Invariant] Filters — Matrix Representations<sup>13</sup> [19:03]
- 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]
- What does the Laplace Transform really tell us? A visual explanation (plus applications)<sup>19</sup> [20:24]  
Nice 3D plot of two poles at  $t=512$ <sup>20</sup> []
- 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>21</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>22</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>23</sup> [27:29]

## 4.2 Section 2: Transfer-Function and Pole-Zero Analysis of Digital Filters, Analog and State Variable Filters, Digitizing Filters

- **Reading:**

- Appendix D (Laplace Transform Analysis)
- Chapter 6 (Z-transform),

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<sup>12</sup><https://www.youtube.com/watch?v=KWhqV95fKRw>

<sup>13</sup>[https://www.youtube.com/watch?v=S7ye\\_HIA\\_hc](https://www.youtube.com/watch?v=S7ye_HIA_hc)

<sup>14</sup><https://www.youtube.com/watch?v=r0fg8eZAKGs>

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

<sup>16</sup>[https://www.youtube.com/watch?v=qE1\\_UzQZnmM](https://www.youtube.com/watch?v=qE1_UzQZnmM)

<sup>17</sup><https://www.youtube.com/watch?v=jNcKGLMHE9A>

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

<sup>19</sup><https://www.youtube.com/watch?v=n2y7n6jw5d0>

<sup>20</sup><https://www.youtube.com/watch?v=n2y7n6jw5d0?t=490>

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

<sup>22</sup>[https://www.youtube.com/watch?v=BULkMAst6\\_U](https://www.youtube.com/watch?v=BULkMAst6_U)

<sup>23</sup><https://www.youtube.com/watch?v=YWJPqHhjf8c>

- Chapter 6 (Transfer Function Analysis)
  - Appendix E (Analog Filters)
  - Laplace Analysis of a Force-Driven Mass
  - Appendix I.3 (Bilinear Transform)
  - Supplementary: Digital State-Variable Filters
  - Supplementary: Interactive Möbius Transformation
- Assignment 2
  - **Lecture Videos (Total Viewing Time  $\approx$  3 Hours):**
    - Transfer Functions, Partial Fraction Expansion, Repeated Poles<sup>24</sup> [44:52]
    - Transfer Functions<sup>25</sup> [50:43]
    - State Variable Analog Filters and Digitization<sup>26</sup> [47:50]
    - Repeated Poles at  $s = 0$ 
      - \* One Pole at DC in the  $s$  Plane<sup>27</sup> [14:17]
      - \* Mechanical Integrator using a Mass<sup>28</sup> [3:46]
      - \* Integrator made by a Spring or Inductor<sup>29</sup> [5:46]
      - \* One Pole at DC in the  $s$  Plane, Continued<sup>30</sup> [1:31]
      - \* Frequency Response of an Integrator<sup>31</sup> [5:05]
      - \* Repeated Poles at DC<sup>32</sup> [4:16]
      - \* General Transfer Function of a Pile of Poles at DC<sup>33</sup> [3:38]
      - \* Impulse Response of a Pile of Poles at DC<sup>34</sup> [3:22]
    - 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>35</sup> [21:39]
    - Bilinear Transform Frequency Mapping, Analog Computers, State Space Formulation, Physical Derivation of Bilinear Transform, State Variable<sup>36</sup> [38:29]

<sup>24</sup><https://www.youtube.com/watch?v=fRLfliem52M>

<sup>25</sup><https://www.youtube.com/watch?v=3C3K7P5xCwg>

<sup>26</sup><https://www.youtube.com/watch?v=CBpVm9Bn7Hs>

<sup>27</sup><https://www.youtube.com/watch?v=DIhH2JIWQeE>

<sup>28</sup><https://www.youtube.com/watch?v=c1TIX2Ybn3U>

<sup>29</sup><https://www.youtube.com/watch?v=qPLyMge71F4>

<sup>30</sup><https://www.youtube.com/watch?v=lqXYMuna3yw>

<sup>31</sup><https://www.youtube.com/watch?v=VLtpw4eD4Uc>

<sup>32</sup><https://www.youtube.com/watch?v=5s6umF7I4T4>

<sup>33</sup>[https://www.youtube.com/watch?v=6\\_VRX5Fvdig](https://www.youtube.com/watch?v=6_VRX5Fvdig)

<sup>34</sup><https://www.youtube.com/watch?v=d6uQYhQteaw>

<sup>35</sup><https://www.youtube.com/watch?v=dEmmtsN-ka4>

<sup>36</sup><https://www.youtube.com/watch?v=GRpAqeVbUWs>

- Bilinear Transform = special case of Moebius Transformation [DON'T MISS THIS ONE!]<sup>37</sup> [2:34]

### 4.3 Section 3: Frequency-Response Analysis, Quality Factor Q, Allpass Filters

- **Reading:**

- Chapter 7 (Frequency Response Analysis)
- First three sections of Chapter 8 (Pole-Zero Analysis)
- Second section of Chapter 9 (Implementation Structures) on parallel/series filter sections
- Appendix B (Elementary Audio Digital Filters) on one/two pole/zero sections, allpass filters, dc blockers, low and high shelf, peaking equalizers
- Appendix C (Allpass Filters), through the first subsection (*i.e.*, the rest is “supplemental” starting at Paraunitary Filters)
- Supplementary: Robust Design of Very High-Order Allpass Dispersion Filters<sup>38</sup>
- Review: Complex Resonators (PDF)<sup>39</sup>
- Review: Comparing Analog and Digital Complex Planes<sup>40</sup> from last quarter

- Assignment 3

- **Lecture Videos**

- Simplest Electrical LPF: RC lowpass, continued; Bode Plot; 3dB Bandwidth<sup>41</sup> [7:45]
- Bandwidth of a Pole, Continuous-Time Complex Resonator and Allpass Filter, Magnitude and Phase Response from Factored Transfer Function<sup>42</sup> [22:16]
- Analog Low-Shelf Filters, High Shelf, Peaking Equalizer, Mapping  $s$  to  $z$ , Bilinear Transform (BLT), BLT Doesn't Alias, BLT Frequency Warping<sup>43</sup> [12:30]
- Bilinear Transform Frequency Scaling, Resonance Preservation; Digitizing an Integrator (Mass), RC Filter, Low Shelf; BLT Stability Preservation, DC Blocker<sup>44</sup> [8:51]
- Supplementary: Shelf Filters in Faust<sup>45</sup> [22:25]
- Analog Filters Reviewed: Transfer Function, Frequency Response, Power Response; Analog Lowpass Design, Maximally Flat Passband, Butterworth Filters<sup>46</sup> [30:46]
- Quality Factor (Q) of a Resonator<sup>47</sup> [7:12]

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<sup>37</sup><https://www.youtube.com/watch?v=JX3VmDgiFnY>

<sup>38</sup>[http://www.dafx.ca/proceedings/papers/p\\_013.pdf](http://www.dafx.ca/proceedings/papers/p_013.pdf)

<sup>39</sup><https://ccrma.stanford.edu/~jos/intro320/Music320B-2018-02-13-ComplexResonators.pdf>

<sup>40</sup>[https://ccrma.stanford.edu/~jos/mdft/Comparing\\_Analog\\_Digital\\_Complex.html](https://ccrma.stanford.edu/~jos/mdft/Comparing_Analog_Digital_Complex.html)

<sup>41</sup><https://www.youtube.com/watch?v=MOBH66RyXZw>

<sup>42</sup><https://www.youtube.com/watch?v=m4zCmvvKFso>

<sup>43</sup><https://www.youtube.com/watch?v=NqYGdcDW3dY>

<sup>44</sup><https://www.youtube.com/watch?v=aaGdgf65PsY>

<sup>45</sup><https://www.youtube.com/watch?v=9RDC4y1ap7E>

<sup>46</sup><https://www.youtube.com/watch?v=doDMmZfEfbg>

<sup>47</sup><https://www.youtube.com/watch?v=V04yxnqBuYk>

- Complex One-Pole Resonator and its Q; Canonical Form of a Biquad (s-plane); Mechanical and Electrical Resonators; Limiters, Compressors, Expanders<sup>48</sup> [39:30]
- Filter Decay Time is about Q Periods<sup>49</sup> [3:16]
- Supplementary: Introduction to Functional Audio Stream (FAUST): Simplest Lowpass, Utilities in Faust’s filter.lib<sup>50</sup> [37:30]
- Supplementary: More FAUST: Testing filters using faust2octave<sup>51</sup> [27:32]

#### 4.4 Section 4: Linear and Minimum Phase Filters, Recursive Digital Filter Design, Butterworth Filters, More on Allpass Filters, More on State Space

- **Reading:**

- Chapter 11 (Filters Preserving Phase)
- Chapter 12 (Minimum-Phase Filters)
- Appendix F (Matrix Filter Representations)
- Appendix G (State Space Filters)
- Supplementary: The Digital Waveguide Oscillator
- State-Space Formulation of Multi-Input, Multi-Output (MIMO) Linear Filters
- Digitizing the State-Variable Filter
- Appendix I (Recursive Digital Filter Design)
- Appendix K (Digital Filtering in FAUST and Pd)  
Supplementary: Audio Signal Processing in FAUST
- **Supplementary:** State-Space Canonical Forms
- **Supplementary:** State Variable Filter used in the ARP2500 analog synthesizer
- Assignment 4

- **Lecture Videos**

- 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<sup>52</sup> [35:19]
- Butterworth Power Response, Analytic Continuation, Butterworth Poles, Matlab `butter()` Function<sup>53</sup> [7:02]
- Example Butterworth Filter of Order 2, Digitization via Bilinear Transform, Frequency Prewarping<sup>54</sup> [18:49]

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<sup>48</sup><https://www.youtube.com/watch?v=zeClzrKUfQU>

<sup>49</sup><https://www.youtube.com/watch?v=kPKZQ16EdcU>

<sup>50</sup><https://www.youtube.com/watch?v=FEf7dpApd6I>

<sup>51</sup><https://www.youtube.com/watch?v=Ao1ZriZi8nY>

<sup>52</sup><https://www.youtube.com/watch?v=pUtUrzVHF3Q>

<sup>53</sup><https://www.youtube.com/watch?v=nhhuAxBUleU>

<sup>54</sup><https://www.youtube.com/watch?v=UcTHnf4B5tU>



- 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<sup>55</sup> [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()`<sup>56</sup> [31:10]
- Supplementary Note on Repeated Poles<sup>57</sup> [4:40]
- Supplementary: MicroModeler Digital Filter Design Tools<sup>58</sup> [5:23]
- Minimum Phase Filters and Signals; Allpass Filters: Poles and Zeros, Graphical Amplitude and Phase Response, Biquad Realization, Phasing; Allpass-Minimum-Phase Decomposition<sup>59</sup> [28:44]
- Allpass Filters in z and s Planes; Instability as Noncausality; Laurent Series; Bilateral DTFT; Cepstrum; Converting Arbitrary Spectra to Minimum-Phase Form<sup>60</sup> [39:13]
- The *State Space* Formulation of Linear Systems [2016 flipped-class review]
  - \* Adding Feedback around the Integrator Chain, Derivation of the State Space Formulation<sup>61</sup> [10:46]
  - \* State Space Formulation, Continued<sup>62</sup> [1:33]
  - \* State Space Overview<sup>63</sup> [11:50]
  - \* Force-Driven Mass Revisited<sup>64</sup> [4:49]
  - \* General Discussion of State Space<sup>65</sup> [8:48]
  - \* Defining State Variables<sup>66</sup> [4:51]
  - \* State Variable Choice Summary<sup>67</sup> [5:14]
  - \* General State Space Model and Digitization via Backward Euler<sup>68</sup> [5:16]
  - \* State Space Converts Nth-Order to Vector First-Order<sup>69</sup> [2:08]
- Supplementary Review (because we already did this in Section 2): State Variable Lowpass, Bandpass, and Highpass

<sup>55</sup>[https://www.youtube.com/watch?v=I0g5r0\\_BgRM](https://www.youtube.com/watch?v=I0g5r0_BgRM)

<sup>56</sup><https://www.youtube.com/watch?v=MxxDS01Ea5o>

<sup>57</sup>[https://www.youtube.com/watch?v=D6\\_AK7mfQnQ](https://www.youtube.com/watch?v=D6_AK7mfQnQ)

<sup>58</sup>[https://www.youtube.com/watch?v=FaG5lPmBY\\_o](https://www.youtube.com/watch?v=FaG5lPmBY_o)

<sup>59</sup><https://www.youtube.com/watch?v=Cj6Vjp6k7NM>

<sup>60</sup><https://www.youtube.com/watch?v=nCwj1VeXQ44>

<sup>61</sup>[https://www.youtube.com/watch?v=a\\_\\_oM8rYPHc](https://www.youtube.com/watch?v=a__oM8rYPHc)

<sup>62</sup><https://www.youtube.com/watch?v=ZN02687Nch0>

<sup>63</sup><https://www.youtube.com/watch?v=Ygq66m9NrDk>

<sup>64</sup><https://www.youtube.com/watch?v=zUibjGb6QQ8>

<sup>65</sup><https://www.youtube.com/watch?v=F0ku7LwHrIO>

<sup>66</sup><https://www.youtube.com/watch?v=45QwWhbJMvU>

<sup>67</sup><https://www.youtube.com/watch?v=LgggKFhh0uo>

<sup>68</sup>[https://www.youtube.com/watch?v=rbrJnknh\\_dU](https://www.youtube.com/watch?v=rbrJnknh_dU)

<sup>69</sup><https://www.youtube.com/watch?v=zd02nQKeaAY>

- \* Normalized Biquad Lowpass Filter, Continuous Time<sup>70</sup> [19:29]
- \* State Variable Realization of Normalized Biquad Lowpass<sup>71</sup> [31:22]
- \* State Variable Filter Lowpass/Bandpass/Highpass<sup>72</sup> [3:00]
- \* State Variable Filter LP/BP/HP Frequency Scaling and Digitization<sup>73</sup> [11:35]

#### 4.5 Section 5: Cross-Overs, Moog VCF, Voice Synthesis, F0 Estimation, Cepstra, Converting to Minimum Phase

- **Reading:**

- *Review all assigned reading to date*, slowing down where needed for full understanding
- **Supplementary:**  
Linkwitz–Riley filter (aka “Butterworth-squared filter”)  
Linkwitz-Riley Crossovers: A Primer  
Active Crossover Networks for Noncoincident Drivers in JAES Volume 24, Issue 1, pp. 2-8, February 1976
- **Supplementary:** Spectral Envelopes via Cepstrum or LPC [from Music 421 overheads]

- **Lecture Videos:**

- Voice Vowel Synthesis in Faust<sup>74</sup> [11:26]
- Moog VCF<sup>75</sup> [23:29]
- Moog VCF Live-Coded in Faust
  - \* Moog VCF Live-Coded in Faust<sup>76</sup> [30:49]
  - \* Moog VCF in Faust, Review<sup>77</sup> [5:02]
  - \* Moog VCF in Faust, Frequency Responses<sup>78</sup> [7:39]
  - \* **Supplementary:** Q-Correction and Gain-Correction Tables<sup>79</sup> [3:38]

All remaining videos are supplementary, either moved beyond the scope of the class, or redundantly covering material already presented.

- Voder<sup>80</sup> [0:43]
- Phonem for iPad by Wolfgang Palm
- Minimum-Phase Spectra Play-List<sup>81</sup>
  - \* Complex and Real Cepstrum, Quefrequency<sup>82</sup> [7:54]

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<sup>70</sup><https://www.youtube.com/watch?v=hjHPMbDa3yk>

<sup>71</sup><https://www.youtube.com/watch?v=9cXaEI0eWuU>

<sup>72</sup><https://www.youtube.com/watch?v=o-Zpot5TKoE>

<sup>73</sup><https://www.youtube.com/watch?v=LgzSnwTFB-0>

<sup>74</sup><https://www.youtube.com/watch?v=GR97SMvS4Fw>

<sup>75</sup><https://www.youtube.com/watch?v=KxBBcNwbZHY>

<sup>76</sup>[https://www.youtube.com/watch?v=WLvpGN\\_UNlA](https://www.youtube.com/watch?v=WLvpGN_UNlA)

<sup>77</sup><https://www.youtube.com/watch?v=VV2e0ChjTrc>

<sup>78</sup><https://www.youtube.com/watch?v=cGuuG1bp1JI>

<sup>79</sup><https://www.youtube.com/watch?v=Q0m0njDsQYY>

<sup>80</sup><https://www.youtube.com/watch?v=e5gQBei-z-c>

<sup>81</sup><https://www.youtube.com/watch?v=Tlk6CLc1PPU&list=PLsBNrwwINMkYNaFpsqn2BVQRZvmbdWu-I&index=0>

<sup>82</sup><https://www.youtube.com/watch?v=Tlk6CLc1PPU>

- \* Mel Frequency Cepstral Coefficients (MFCC); Bark and Equivalent Rectangular Bandwidth (ERB) Psychoacoustic Frequency Scales based on Critical Bands of hearing<sup>83</sup> [7:54]
- \* Complex Cepstrum Derived; Converting Mixed-Phase Signals to Minimum Phase<sup>84</sup> [5:39]
- \* Series Expansion of Log of  $1/(1-x)$ <sup>85</sup> [7:57]
- \* Series Expansion of Log Transfer Function in Factored Form<sup>86</sup> [5:26]
- \* Contribution of Zeros to the Complex Cepstrum<sup>87</sup> [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<sup>88</sup> [9:14]
- \* Nonparametric Cepstral Folding Method in Matlab: `minphasespec()`, `fold()`, `invfreqz()`<sup>89</sup> [6:11]
- \* Review of another Cepstral Folding Example<sup>90</sup> [19:08]
- \* Minimum Phase Conversion by Spectral Factorization or Cepstral Method<sup>91</sup> [5:45]
- \* Minimum Phase Conversion by the Cepstral Method, Continued<sup>92</sup> [12:10]
- \* Cepstral Method Code, then CollideFX Demo by Chet Gnegy<sup>93</sup> [55:51]

## 4.6 Final Exam

**Final Exam:** Tuesday, March 20, 2018, 3:30-6:30 PM, in the CCRMA Classroom

- The exam will cover readings, homework problems, and laboratory assignments.
- The exam will be *closed book*, except that you may bring an 8.5" by 11" sheet of paper, covered front and back with handwritten notes.
- No calculators allowed (you shouldn't need one).

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<sup>83</sup><https://www.youtube.com/watch?v=201BBFeQG0E>

<sup>84</sup><https://www.youtube.com/watch?v=0H1z40W-7UA>

<sup>85</sup><https://www.youtube.com/watch?v=wrs1b9U7HaI>

<sup>86</sup>[https://www.youtube.com/watch?v=x3gCA\\_rj13k](https://www.youtube.com/watch?v=x3gCA_rj13k)

<sup>87</sup><https://www.youtube.com/watch?v=niY8EA4-peA>

<sup>88</sup>[https://www.youtube.com/watch?v=-\\_yA01UTCko](https://www.youtube.com/watch?v=-_yA01UTCko)

<sup>89</sup><https://www.youtube.com/watch?v=PTx0capBmHU>

<sup>90</sup><https://www.youtube.com/watch?v=V7K4rmT94PE>

<sup>91</sup><https://www.youtube.com/watch?v=7GcCkMcqVao>

<sup>92</sup><https://www.youtube.com/watch?v=5RNeaaFxfVg>

<sup>93</sup><https://www.youtube.com/watch?v=nkt3bR04tI4>