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Music 420A: Signal Processing Models in Musical Acoustics

This course is presently offered only as a self-paced independent study at CCRMA (sign up for Music 220D).

1 Course Overview

Music 420A is about computational electroacoustic modeling for digital audio effects, sound synthesis, and signal processing for physical modeling in general.

1.1 When, Where, Who

This course is presently only offered as a self-paced independent study at CCRMA (sign up for Music 220D).

1.2 Prerequisites

The prerequisites for Music 420A consist of a prior first course in signal processing and elementary dynamics, together with programming in C++ and MATLAB or Octave or Python. Familiarity with UNIX-style programming tools (make, bash, etc.) is desirable.

1.3 Important Pointers

The course schedule and outline2 in §2 on page 2 (also reachable from the class home page3) lists all topics covered, lecture overheads, reading assignments, lecture videos, and hw/lab assignments.

1.4 Textbook

The text for this course is Physical Audio Signal Processing4 by JOS:

- Available for free online in HTML format.
- Printed hardcopies5 also available.
- Reading assignments will be specified in the course schedule and outline.

1.5 Prerequisite-Level Reading

This course assumes the student is familiar with elementary signal processing on the level of the following textbooks:

- Mathematics of the Discrete-Time Fourier Transform (DFT)6 — prerequisite material pertaining to the DFT (Music 320 text 1)

1https://exploreCourses.stanford.edu/search?q=music+420a
2https://ccrma.stanford.edu/~jos/intro420/Schedule_Assignments.html
3https://ccrma.stanford.edu/~jos/intro420/Schedule_Assignments.html
4https://ccrma.stanford.edu/~jos/pasp/
5https://ccrma.stanford.edu/~jos/pasp/pasp-hardcopy.html
6https://ccrma.stanford.edu/~jos/mdft/
• **Introduction to Digital Filters**— prerequisite material in the area of digital filtering and linear systems theory (Music 320 text 2)

## 2 Schedule

Below is our current schedule, with pointers to all reading assignments, lecture overheads, and theory/lab exercises for the course. Anything marked “Supplementary” is not required for the course, but may be of interest.

• Schedule Summary by Week:

  1. Intro and Overview, Prerequisites Review
  2. Digitizing Mass-Spring Systems, Parallel and Series Connections
  3. Finite Difference Schemes Backward/Forward Euler, Bilinear Transform
  4. Finite Difference Schemes, State Space Models, State Variable Filters
  5. Mass-Spring Chain and Traveling Waves below Cutoff
  6. Acoustic Modeling with Digital Delay, Comb Filters, Allpass Filters
  7. Interpolation of Delay Lines and Sampled Signals
  8. Wave Scattering
  9. Wave Digital Filters
  10. Applications, Review, Worked Problems

• Week 1: Course Intro (this document), Intro to Demos, Demos (interactive demos), Basic physics and signal-processing demos (HTML) (PDF), History of Virtual Musical Instruments Based on Physical Modeling (video), Laplace Transform, Comparison of s and z planes

  – **Reading:**
    * “MUS420A Administrative Info” (this document)
    * Chapter 1 of **PASP**: “Introduction to Physical Signal Models”
    * Review as needed elementary spectrum analysis and digital filter analysis.
    * Review Matlab, as needed.
  
  – **Lecture Videos:**
    * Overview of Signal Modeling Methods [39:34]
    * Related Research Overviews [54:59]

  – **Supplementary Tutorial Video on Laplace and Fourier Transforms:**
    * What does the Laplace Transform really tell us? A visual explanation (plus applications) [20:24]

  – Exercise 1

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\(^7\)https://ccrma.stanford.edu/~jos/filters/
• Week 2: Finite Difference Schemes

  - **Reading:**
    * Chapter 1 of *PASP* entitled “Introduction to Physical Signal Models”
    * Chapter 7 of *PASP* entitled “Lumped Models”
    * Supplementary: *Dynamical Analogies* by Harry F. Olson, 1943
    * Supplementary: Simple Friction Model
      “Friction is in fact a very complex phenomenon which cannot be represented by a simple model. Almost every simple statement you make about friction can be countered with specific examples to the contrary.”
    * Supplementary: More Advanced Friction Modeling

  - **Lecture Videos:**
    * Supplementary: “State-Space Canonical Forms”
  
- Ex#2

• Week 3: Finite Difference Schemes

  - **Reading:**
    * Lumped Models
    * Finite-Difference Schemes
    * If needed: Introduction to Matrices
    * State Space Filters
    * **Supplementary:** Germain and Werner: Design Principles for Lumped Model Discretisation Using

  - **Lecture Videos:**
    * Finite-Difference-Scheme Error Order, State Space Intro, Elementary Impedances [40:45]
    * State Space Intro Concluded, Elementary Impedances, Mass, Spring, Dashpot [36:14]
    * Continued (unfortunately containing five short audio dropouts) [12:34]
  
- Ex#3

• Week 4: Finite Difference Schemes, State Variable Filters

  - **Reading (continuing from last week):**
    * Lumped Models
    * Digital State-Variable Filters,
    * Finite-Difference Schemes
    * If needed: Introduction to Matrices
    * State Space Filters

  - **Lecture Videos:**
    * Dashpots, Friction [13:20]
• One Ports, Positive Real Immittances, Schur Reflectances, Modeling a Passive Guitar Bridge [56:26]
• State Space Models [24:22]
• State Space Models, Continued [1:02:31]

• Week 5: Mass-Spring Chain, Delay Lines, Comb Filters, TDLs, Allpass Filters
  – Reading:
    * Lumped Models,
    * Chapter 2 of PASP entitled “Acoustic Modeling with Delay.”
  – Physical Animation Demos:
    * Waves on a String
    * Triply Plucked String
    * Traveling Waves and their Sum
  – Lecture Videos:
    * Segue from Lumped to Distributed Modeling: The Mass-Spring Chain, Ideal String Wave Equation [40:53]
    * Traveling-Wave Solution of the Wave Equation [4:56]
    * Physics of Simple Vibrating Strings [30:59]
    * Alternate Wave Variables, Wave Impedance, Force Waves [30:42]
    * Force Waves, [39:39]
  – Ex#4

• Week 6: Delay Lines, Comb Filters, TDLs, Allpass Filters, Interpolating Delay Lines
  – Reading:
    * Chapter 4 of PASP entitled “Delay/Signal Interpolation”
    * Room Acoustics Modeling with Interactive Visualizations, by Lauri Savioja
  – Lecture Videos:
    * Delay Line Interpolation, First-Order Linear and Allpass Interpolation [25:47]
    * Ideal Bandlimited (Sinc) Interpolation, Windowed Sinc Interpolation, Nth-Order Polynomial (Lagrange) [1:25:15]
    * Fast FIR Filter Structures for Lagrange Interpolation [20:12]
    * Interpolator Derivation Using Newton’s Backward Difference Formula [24:34]
    * Time-Varying Delay Effects [44:36]
    * The Leslie Effect [20:11]
  – Ex#5

• Week 7: Interpolating Delay Lines, Commuted Synthesis, Impedance and One-Ports, Simple String Models, Scattering Junctions
  – Reading:
1. Chapter 6 of **PASP** entitled “Digital Waveguide Models”
2. First 8 pages of Chapter 9 of **PASP** entitled “Virtual Musical Instruments”
3. Supplementary: Diode Clipper Simulation

**Lecture Videos:**
* Idealized Vibrating Plucked/Struck String Models [47:24]
* Karplus-Strong Algorithm, Simple String Damping, Loop Filter Identification [22:35]
* F0 Measurement by Harmonic Comb, Hard Clipping, Soft Clipping, Cubic Nonlinearity, Oversampling [40:22]

- **Week 8:** Scattering Junctions, Ideal String Struck by a Mass

  **Reading:**
  * Chapter 9 of **PASP** entitled “Virtual Musical Instruments”
  * Appendix F of **PASP** entitled “Digital Waveguide Theory”

  **Lecture Videos:**
  * Wave Scattering [1:20:03]
  * Passive Signal Processing, Digital Waveguide Mesh [57:10]
  * First Look at Wave Digital Filters [21:33]
  - Ex#6

- **Week 9:** Wave Digital Filters (WDF)

  **Reading:**
  * Appendix of **PASP** entitled “Wave Digital Filters”
  * Simulating Guitar Distortion Circuits Using Wave Digital and Nonlinear State-Space Formulations
  * Supplementary: David Yeh Thesis
  * Supplementary: Werner et al. DAFx15 I
  * Supplementary: Werner et al. DAFx15 II

  **Lecture Videos:**

  **More Lecture Videos:**
  * Wave Digital Filters [1:35:04]
  * Supplementary: Khan Academy: Solving a Nonlinear Diode+Resistor+Battery Circuit [8:06]

- **Week 10 (All Supplementary):** Project Presentations, Current Research, Special Topics, Applications, Demos, David Yeh WDF Tutorial, Piano Modeling, Wave Digital Piano Hammer, Physical Model Overview, Related Research (PDF), Spectral Modeling (PDF)
  - Wave Digital Filters
  - Mark Rau Recent Research
  - Jatin Chowdhury Nonlinear Filters
  - Brendan Larkin Adaptive Filters