Lecture 1: Course Introduction

1. Course Structure
2. DSP: The Short-Time Fourier Transform

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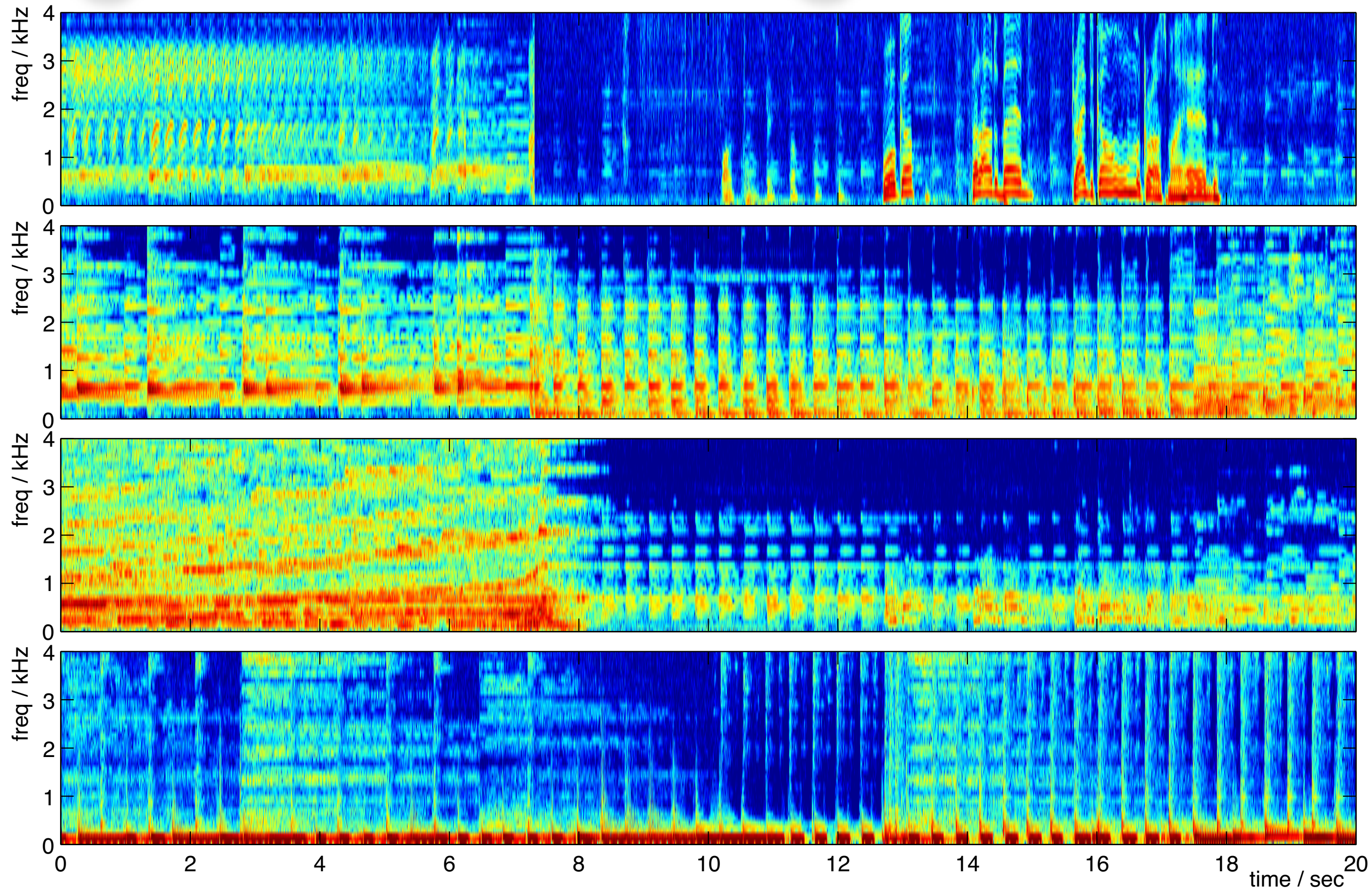
Signal Processing and Music



- Music is a very rich signal
- Signal Processing can expose some of it
- We want to get inside it

1. Course Goals

- Survey of applications of signal processing to music audio
    - music synthesis
    - music/audio processing (modification)
    - music audio analysis
- Connect basic DSP theory to sound phenomena and effects
- Hands-on, live investigations of audio processing algorithms
    - using Matlab, Pd, ...

Course Structure

- **Two weekly sessions**
  - Monday:
    presentations, practical exposition, discussion
  - Wednesday:
    presentations, practical, sharing

- **Grade structure**
  - 20% practicals participation
  - 10% one presentation
  - 30% three mini-project assignments
  - 40% one final project

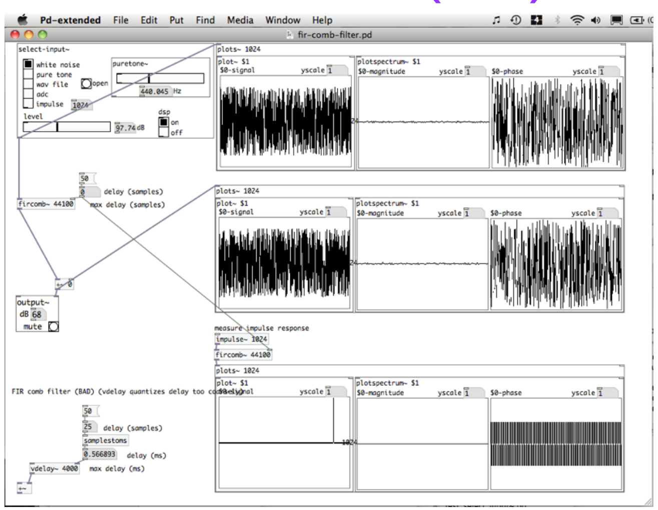
Flipped Classroom

- Video Lectures are required viewing before Monday session
  - 30-50 mins each
  - recorded in 2013
  - bring one question (at least) to class
  - pop quizzes

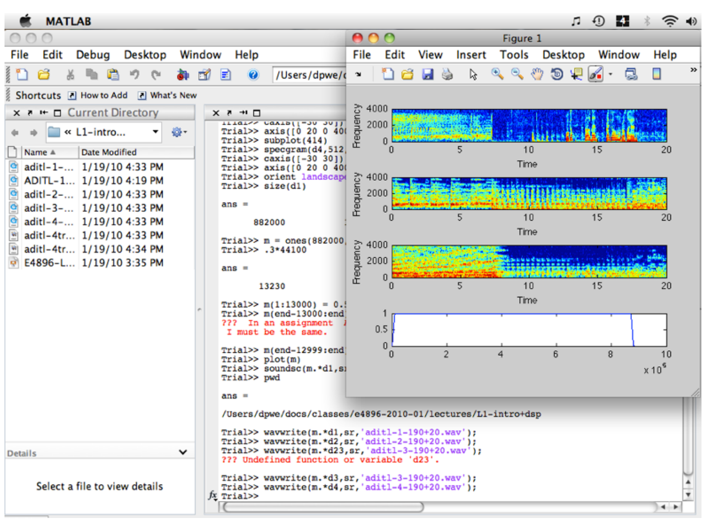
Hands-on Practicals

- Music Signal Processing involves connecting algorithms with perceptions
- Our goal is to be able to 'play' with algorithms to feel how they work
  - In class, on laptops, in small groups
- We will use several platforms:

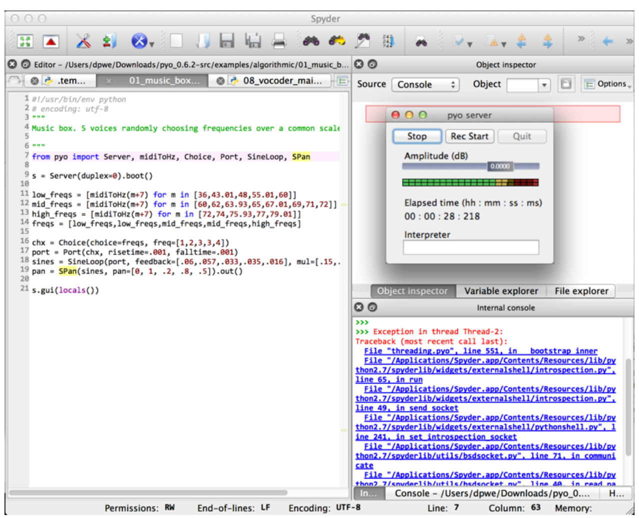
PureData (Pd)



Matlab



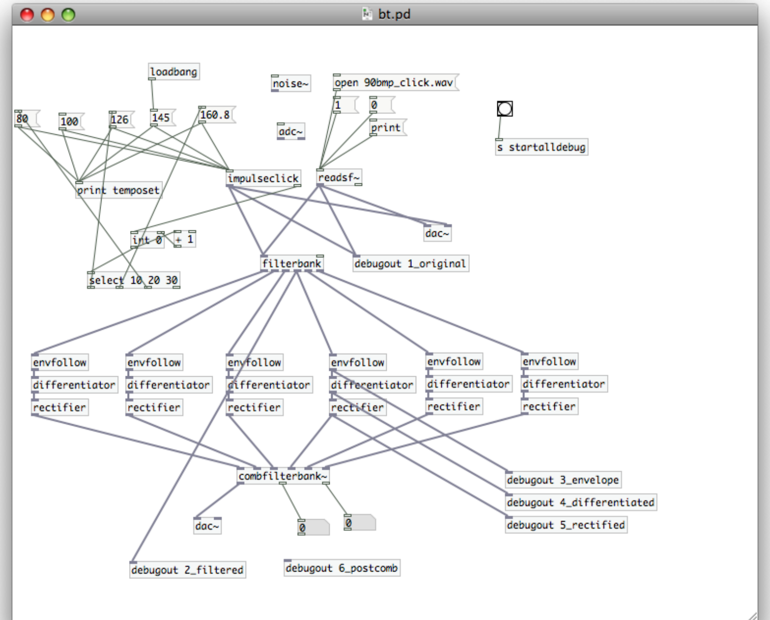
Python



Projects

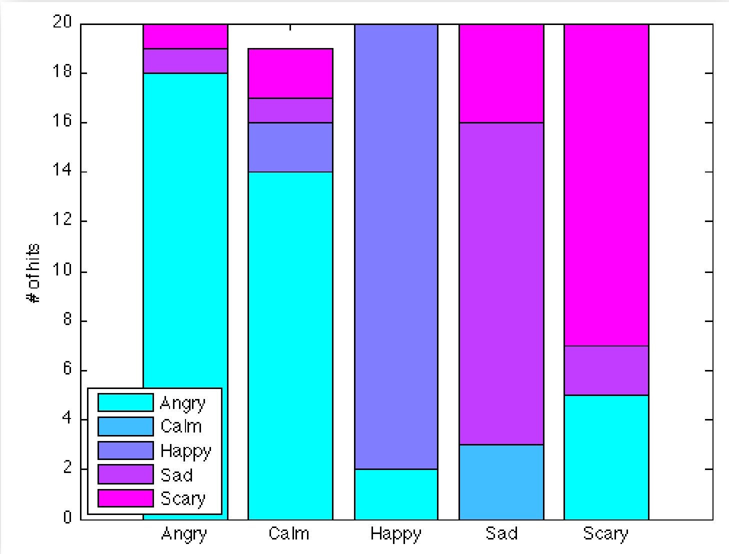
- There will be 3 "mini projects" assigned
  - approx. week 3, week 5, week 7
  - provide basic pieces, but open-ended
  - involve implementation & experimentation
- Also, Final project
  - on a topic of your choice
  - implement some kind of music signal processing
  - due at end of semester
- Good projects ...
  - ... start with clear goals
  - ... apply ideas from class
  - ... evaluate performance & modify accordingly
- Could continue into summer...

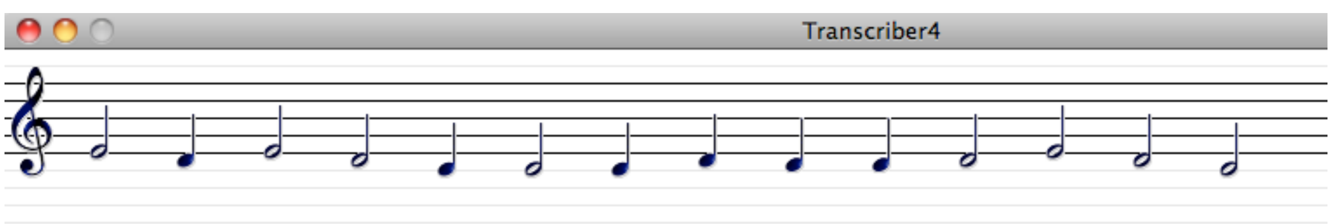
Project Examples



- Beat Tracking

- Mood Classification

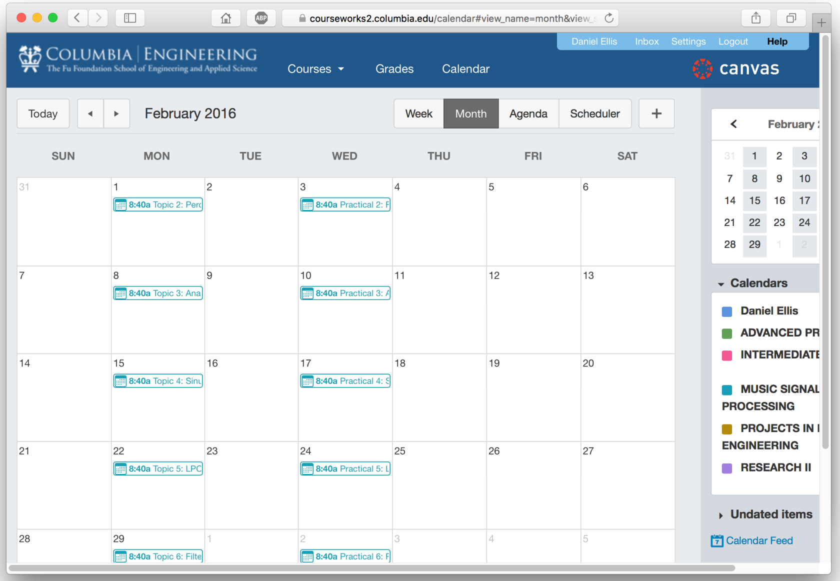




- Music Transcription

Presentations

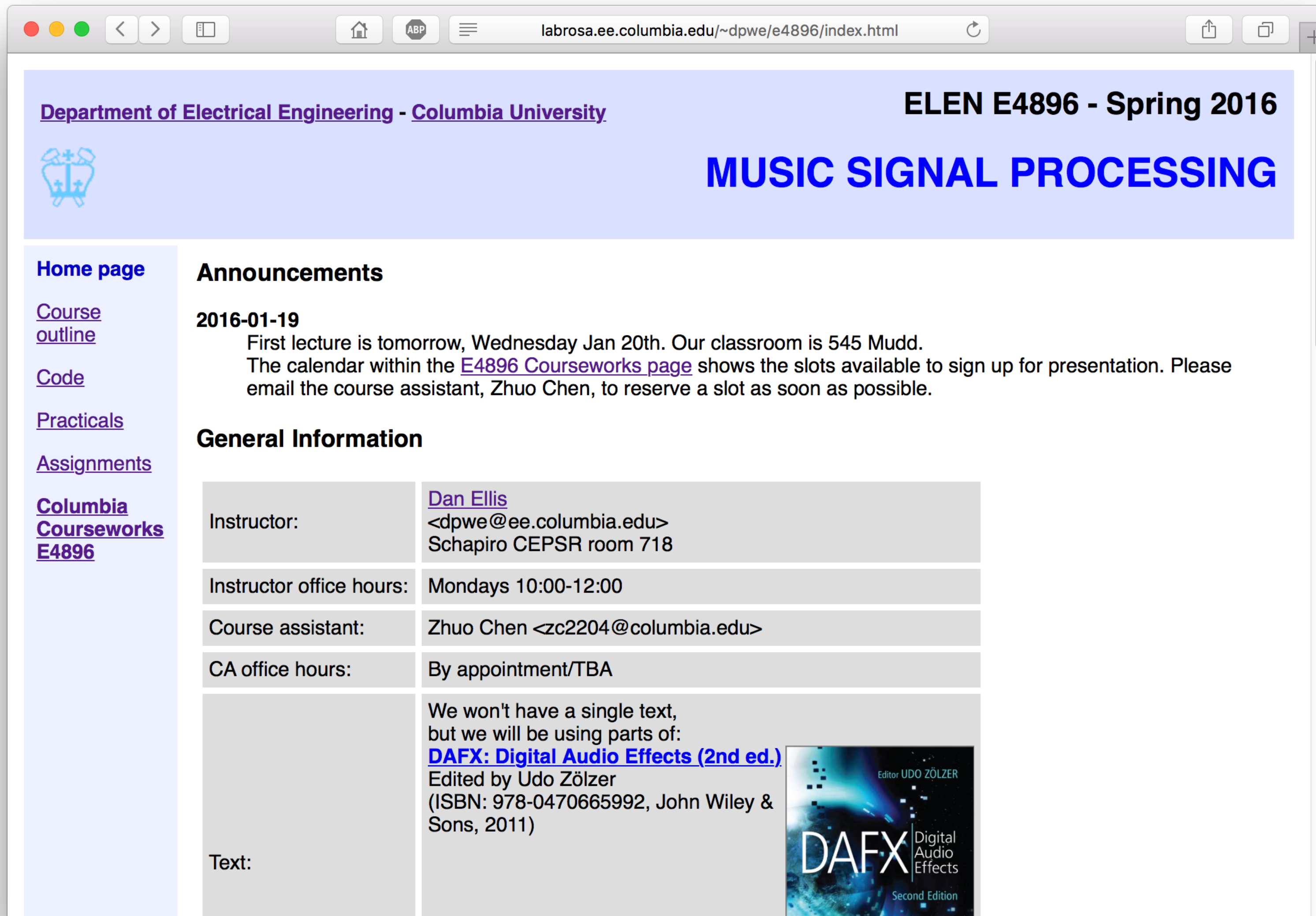
- Everyone will make at least one in-class presentation
  - e.g. presentation of a relevant paper
  - ... or your latest mini-project
  - ... or just something you're curious about
- We will assign time slots first-come-first served
  - slots each class
  - check course calendar to choose a time
  - email TA



- Encourage discussion
  - informal presentations of practical findings

Web Site

- Information distributed via:
  http://www.ee.columbia.edu/~dpwe/e4896/

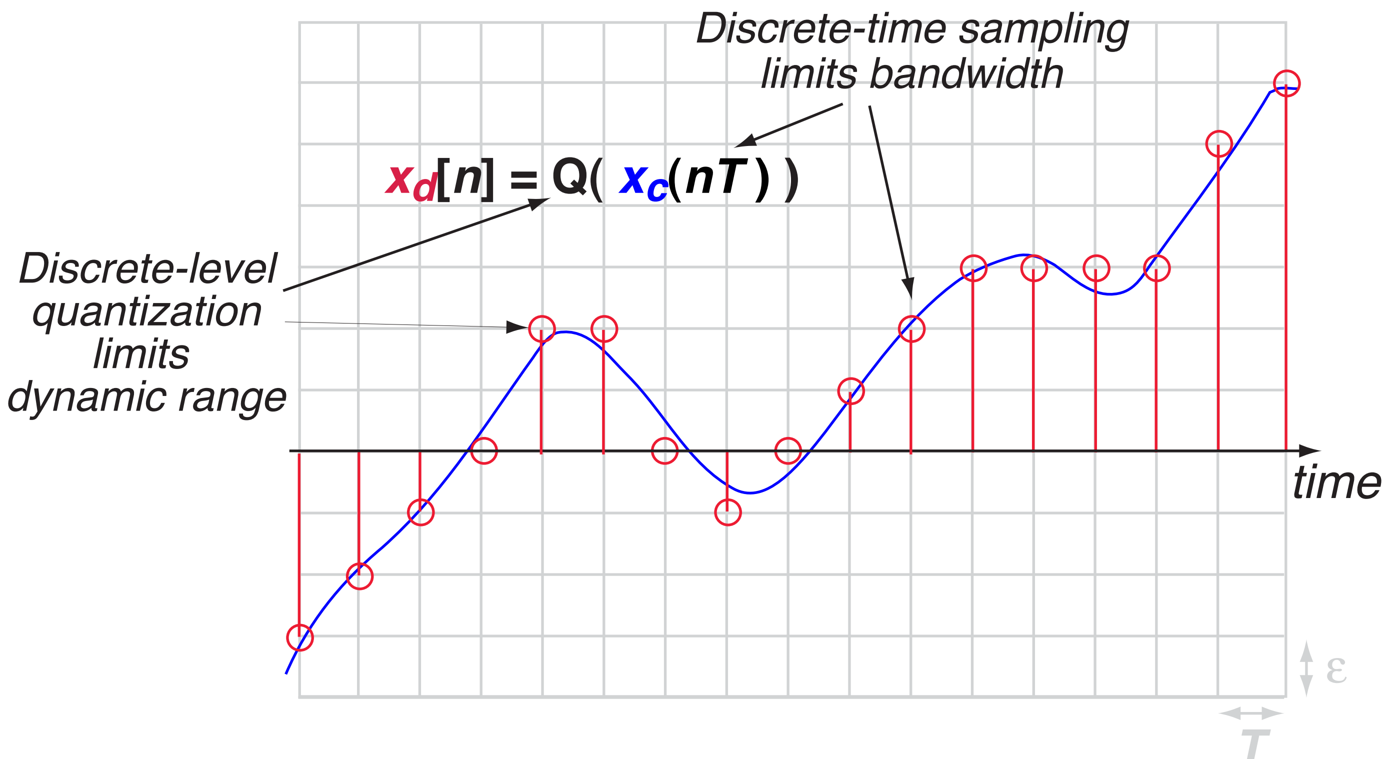


Course Outline

Jan 20: Intro	Mar 07: Pitch tracking
Jan 25: Acoustics	Mar 21: Time & pitch scaling
Feb 01: Perception	Mar 28: Beat tracking
Feb 08: Analog synthesis	Apr 04: Chroma & Chords
Feb 15: Sinusoidal models	Apr 11: Audio alignment
Feb 22: LPC models	Apr 18: Music fingerprinting
Feb 29: Filtering & Reverb	Apr 25: Source separation

- Anything missing?

2. Digital Signals



- Sampling interval T
- Sampling frequency $\Omega_0 = 2\pi/T$
- Quantizer $Q(x) = \epsilon \cdot \mathrm{round}(x/\epsilon)$

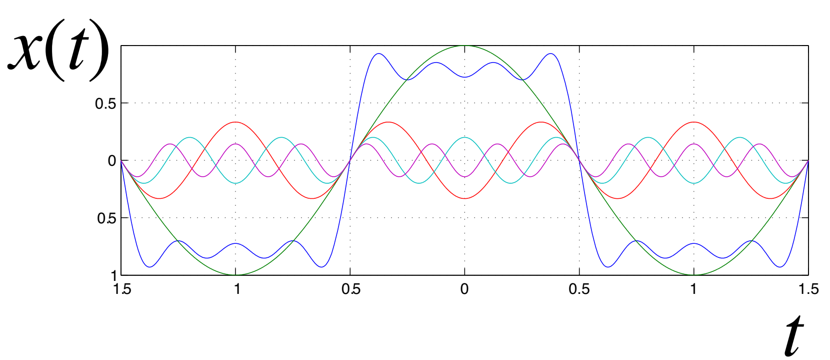
Fourier Series

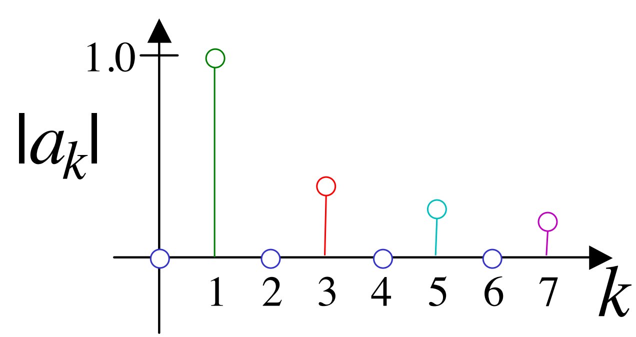
- Observation:
  Any periodic signal can be constructed from sinusoids at integer multiples of the fundamental frequency

$$x(t) = x(t+T) \quad \Leftrightarrow \quad x(t) \approx \sum_{k=0}^{M} a_k \cos\left(\frac{2\pi k}{T} t + \phi_k\right)$$

- E.g., square wave

$$\phi_k = 0; a_k = \begin{cases} (-1)^{\frac{k-1}{2}} \frac{1}{k} & k = 1, 3, 5, \ldots \\ 0 & \text{otherwise} \end{cases}$$





Fourier Transform

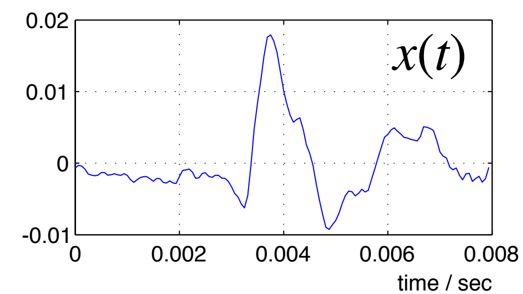
- Complex form of Fourier Series + analysis

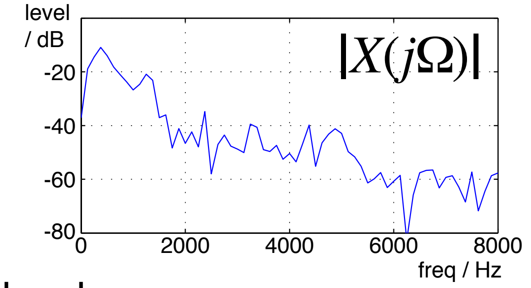
$$x(t) \approx \sum_{k=-M}^{M} c_k e^{j\frac{2\pi k}{T}t} \qquad c_k = \frac{1}{T}\int_{-T/2}^{T/2} x(t) e^{-j\frac{2\pi k}{T}t} dt$$

- Let $T \rightarrow \infty$
  Harmonics become infinitely close:

$$x(t) = \frac{1}{2\pi}\int_{\infty}^{\infty} X(j\Omega) e^{j\Omega t} d\Omega$$

$$X(j\Omega) = \int_{\infty}^{\infty} x(t) e^{-j\Omega t} dt$$



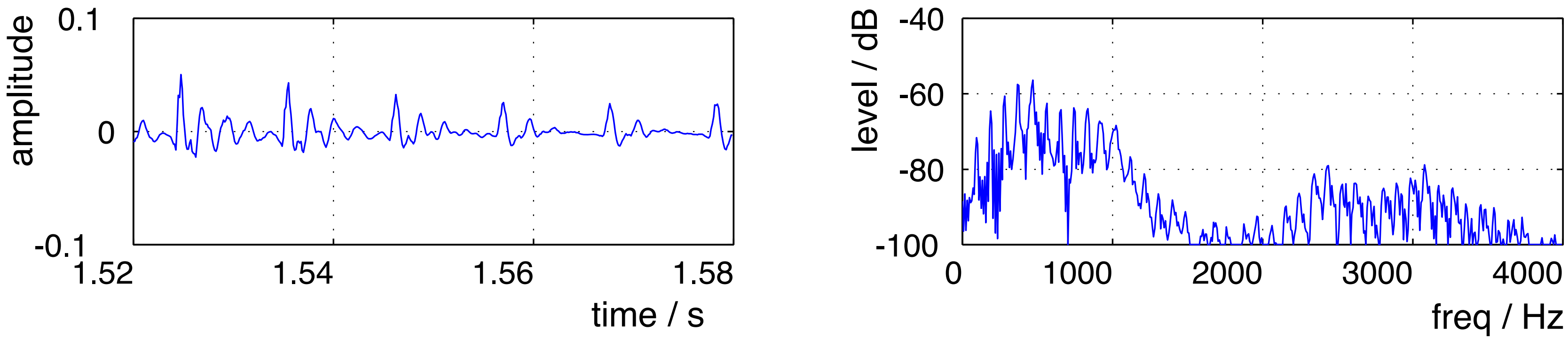


  - $x(t), X(j\Omega)$ are equivalent, dual descriptions

Spectrum of Periodic Sounds

- If sound is (nearly) periodic (i.e., pitched), Fourier Transform approaches Fourier Series

$$x(t) \approx x(t+T)$$
$$X(j\Omega) \approx \sum_k c_k \delta(\Omega - k\tfrac{2\pi}{T})$$



- n.b.: $|X(j\Omega)|$ plotted in log units:

$$dB(x) = 20\log_{10}(x)$$

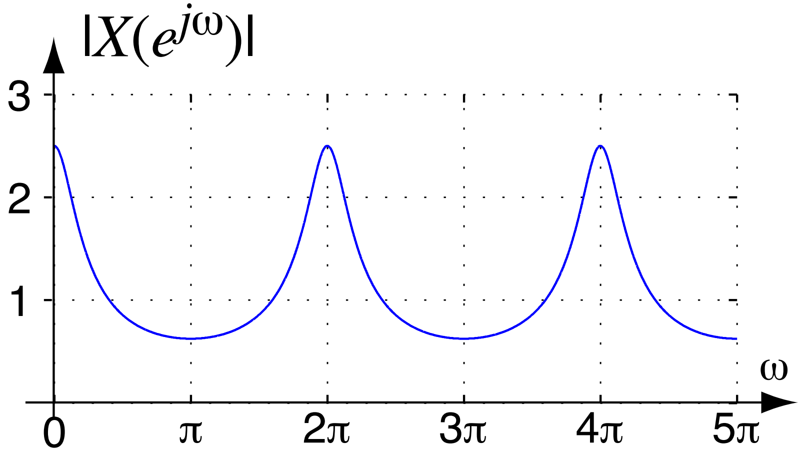
Discrete-Time Fourier Transf. (DTFT)

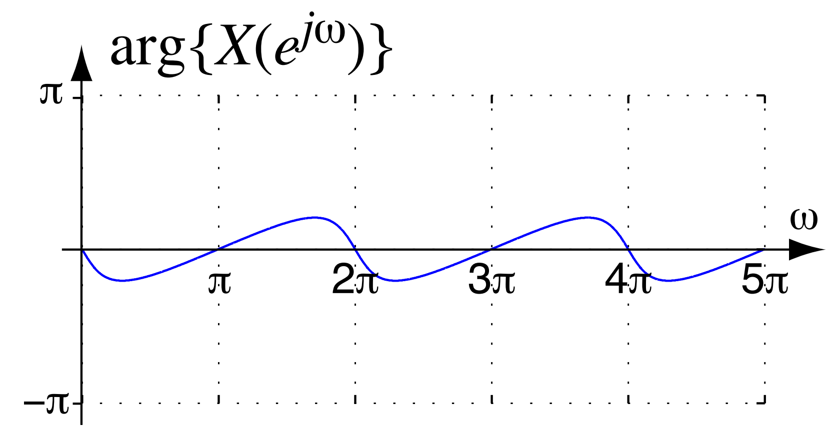
- Sampled $x[n] = x(nT)$ has same FT form

$$x[n] = \frac{1}{2\pi}\int_{-\pi}^{\pi} X(e^{j\omega})e^{j\omega n}d\omega$$

$$X(e^{j\omega}) = \sum_{n=-\infty}^{\infty} x[n]e^{-j\omega n}$$

- ... but results in spectrum with period 2π:





Discrete Fourier Transform (DFT)

- N-point finite-length sampled signal
  - the kind you can have on a computer!

$$x[n] = \frac{1}{N}\sum_{k=0}^{N-1} X[k] W_N^{nk}$$

$$X[k] = \sum_{n=0}^{N-1} x[n] W_N^{-nk}$$

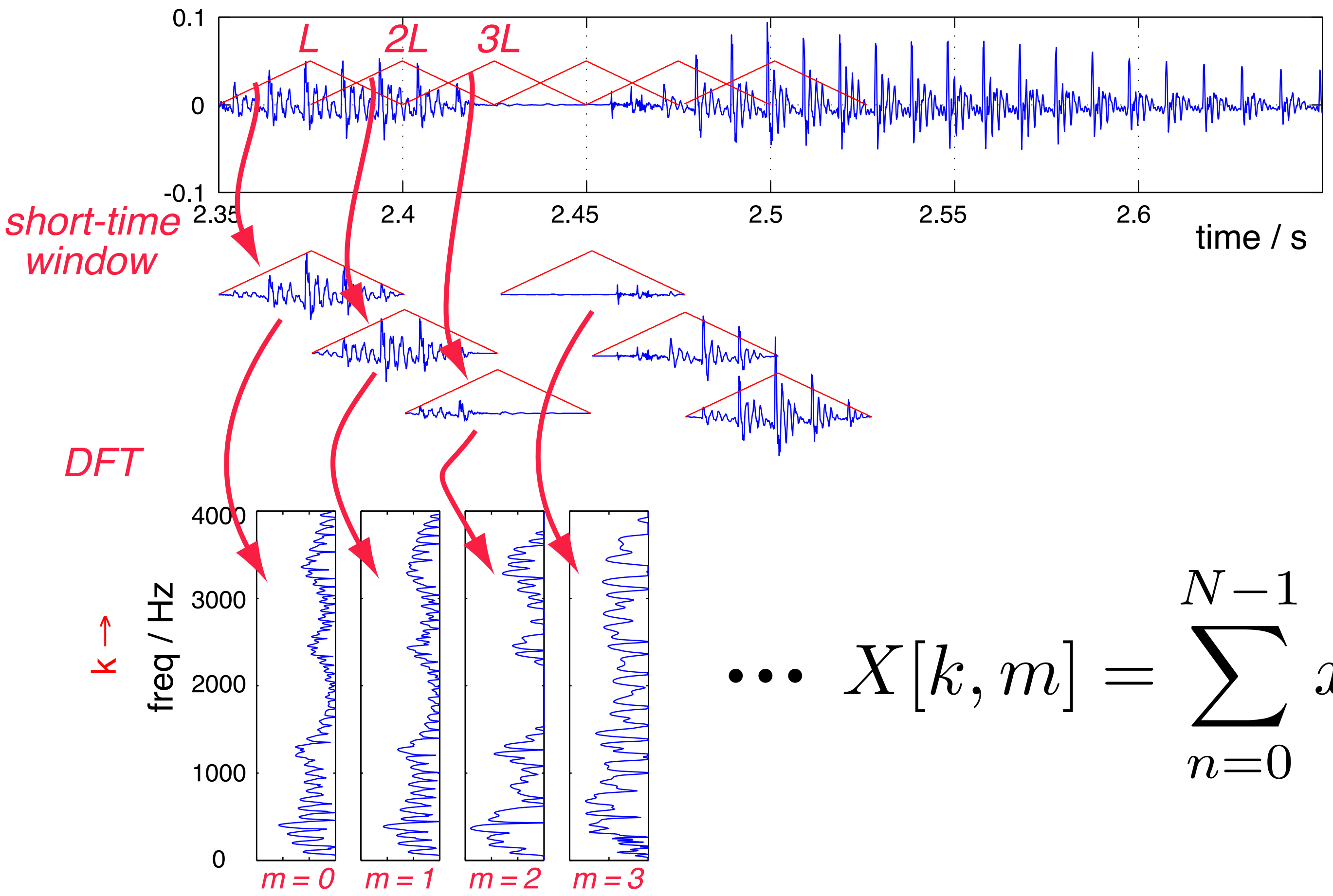
$$W_N = e^{-j\frac{2\pi}{N}}$$

- Just a matrix-multiply between vectors

$$\begin{bmatrix} X[0] \\ X[1] \\ X[2] \\ \vdots \\ X[N-1] \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \\ 1 & W_N^1 & W_N^2 & \cdots & W_N^{(N-1)} \\ 1 & W_N^2 & W_N^4 & \cdots & W_N^{2(N-1)} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & W_N^{(N-1)} & W_N^{2(N-1)} & \cdots & W_N^{(N-1)^2} \end{bmatrix} \begin{bmatrix} x[0] \\ x[1] \\ x[2] \\ \vdots \\ x[N-1] \end{bmatrix}$$

Short-Time Fourier Transform

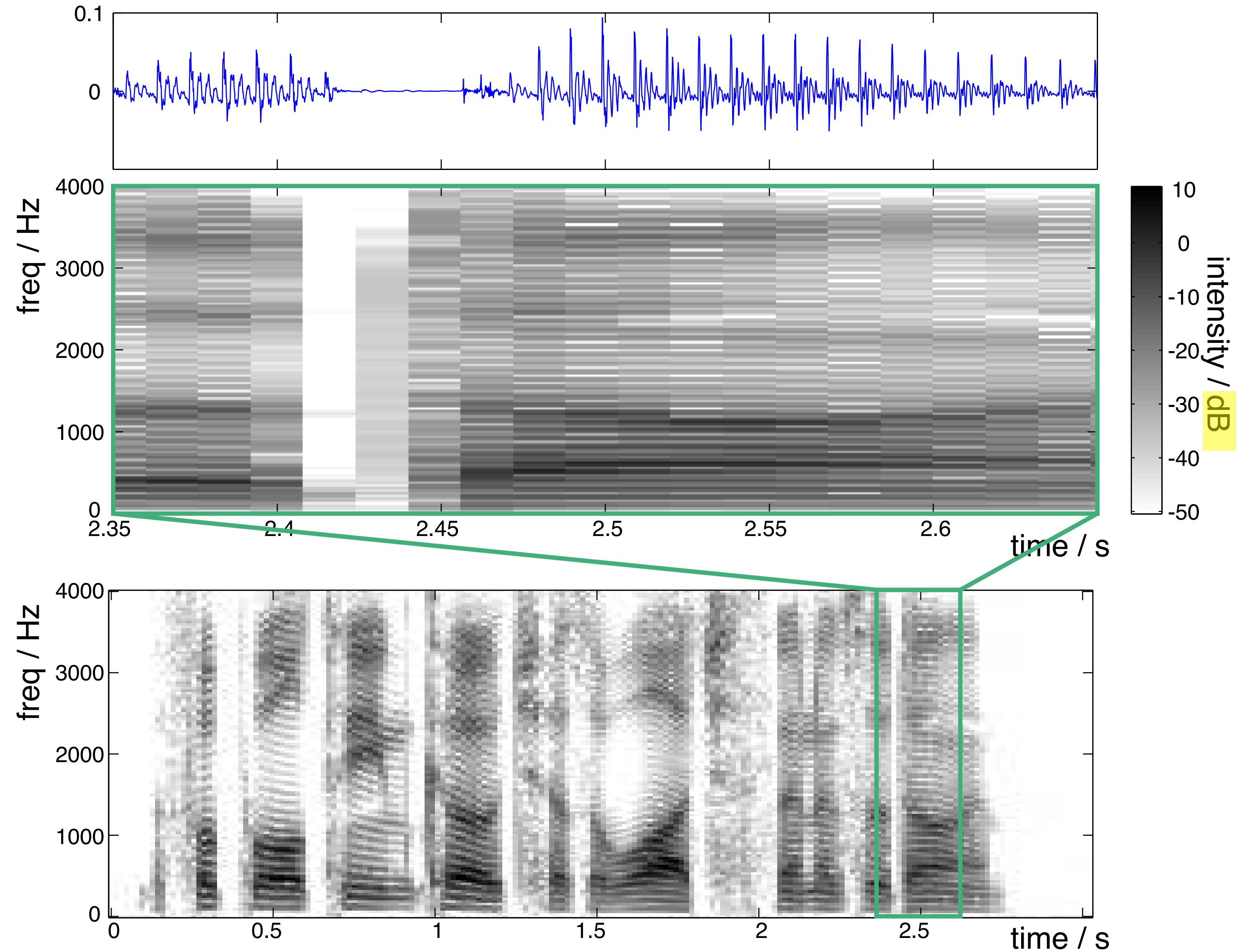
- **To localize energy in time and frequency...**
  - chop signal into N-point windows every L points
  - take DFT of each one



... $$X[k,m] = \sum_{n=0}^{N-1} x[n+mL]\,w[n]e^{-j\frac{2\pi kn}{N}}$$

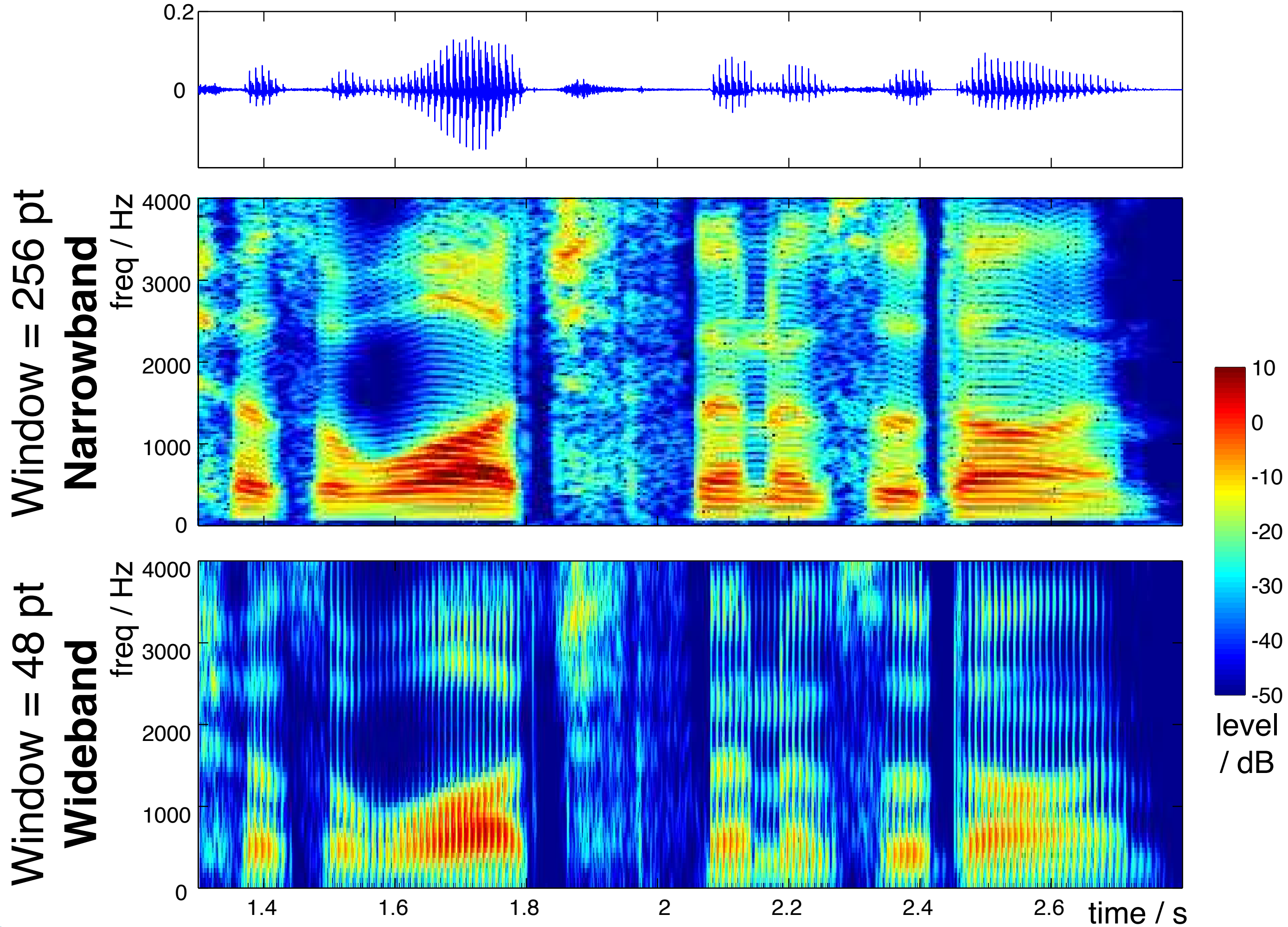
The Spectrogram

- Plot STFT $|X[k, m]|$ as a grayscale image

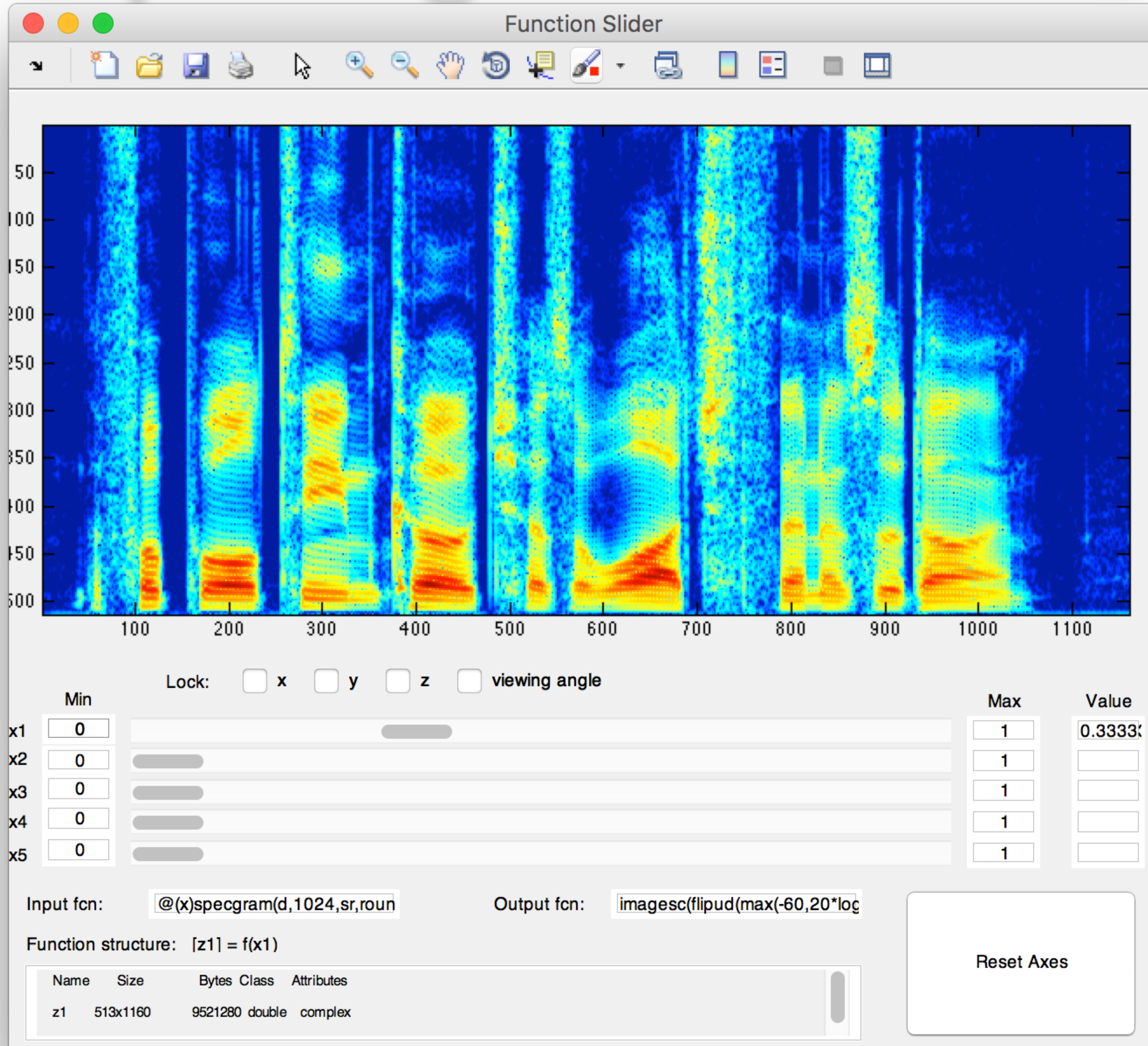


Time-Frequency Tradeoff

- Shorter window
  → better resolution of time detail
  → worse resolution of frequency detail

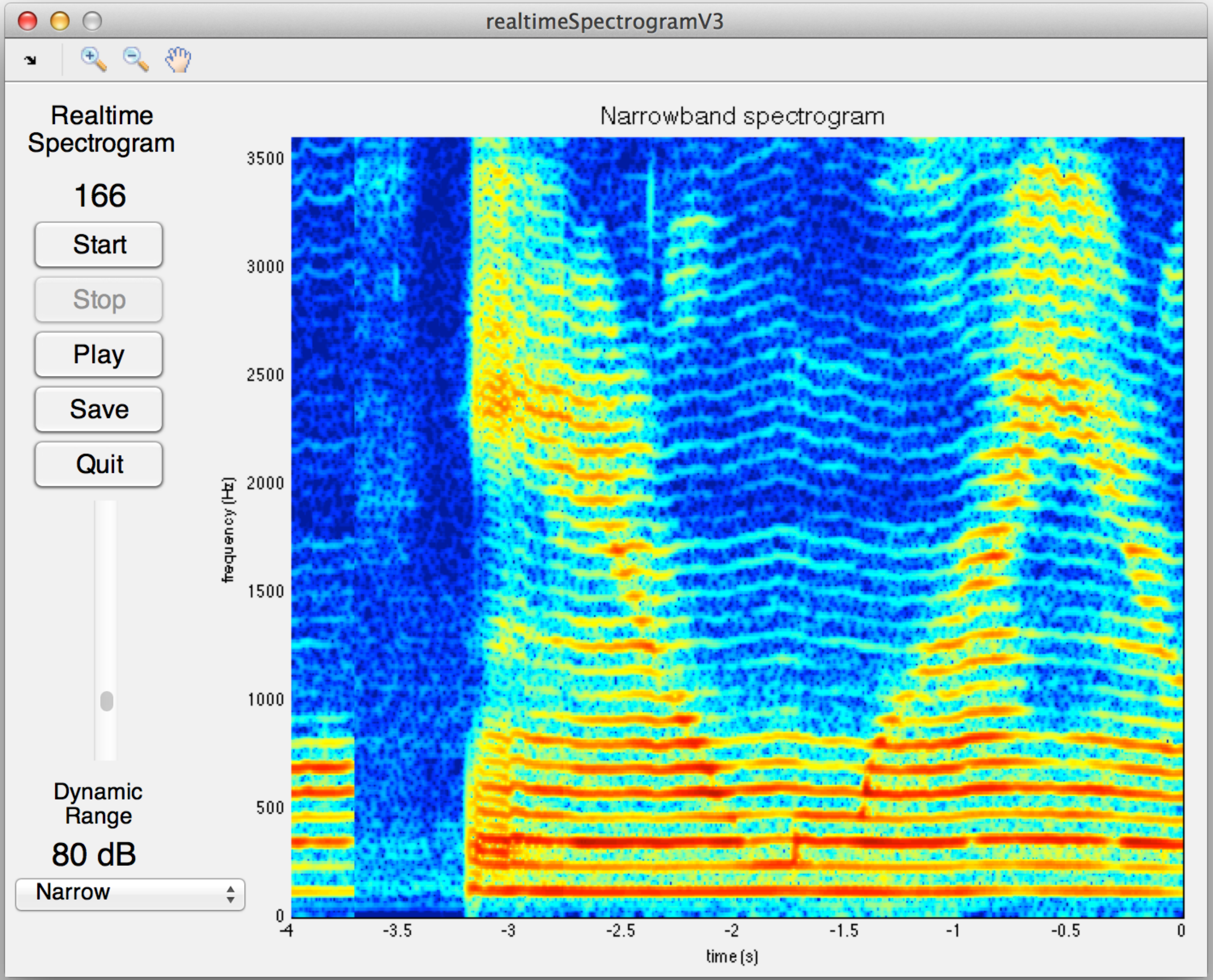


Spectrogram in Matlab



- https://www.ee.columbia.edu/~dpwe/e4810/matlab/M14-fft.diary

Live Matlab Spectrogram



- http://www.wakayama-u.ac.jp/~kawahara/MatlabRealtimeSpeechTools/

Summary + Assignment

- **Music Signal Processing**
  - synthesis, modification, analysis
  - hands-on investigation
- **Course**
  - participation, practicals, projects, presentations
- **Digital Signal Processing**
  - signals on computers
  - Fourier analysis & spectrogram
- **Assignment**
  - Watch Acoustics video & prepare question
  - Do Pd tutorial http://en.flossmanuals.net/pure-data/ through to "Amplitude Modulation"