Speech Technology: A Practical Introduction

Topic: Spectrogram, Cepstrum and Mel-Frequency Analysis

Kishore Prahallad
Email: skishore@cs.cmu.edu

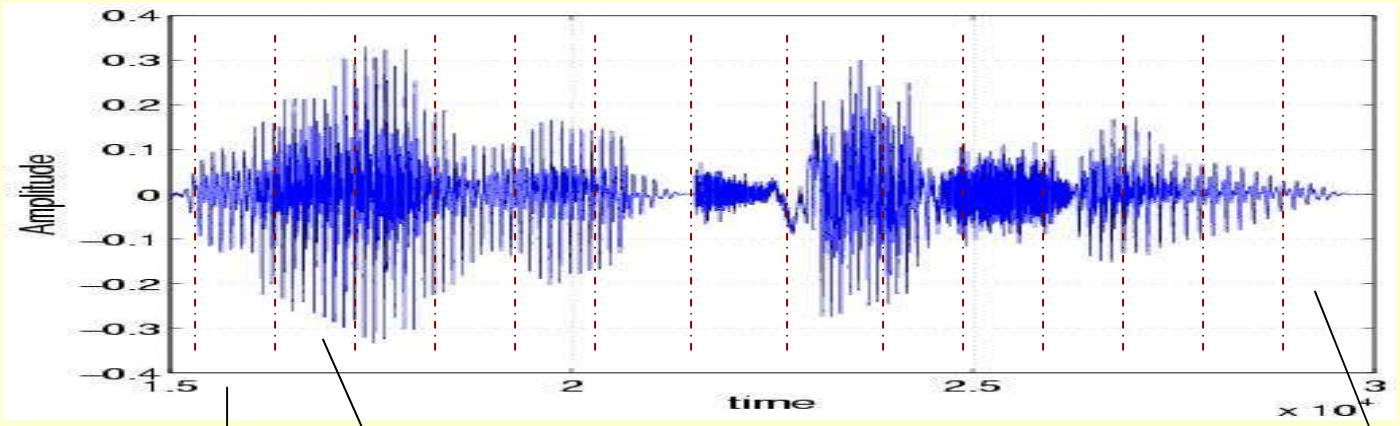
Carnegie Mellon University
&
International Institute of Information Technology Hyderabad

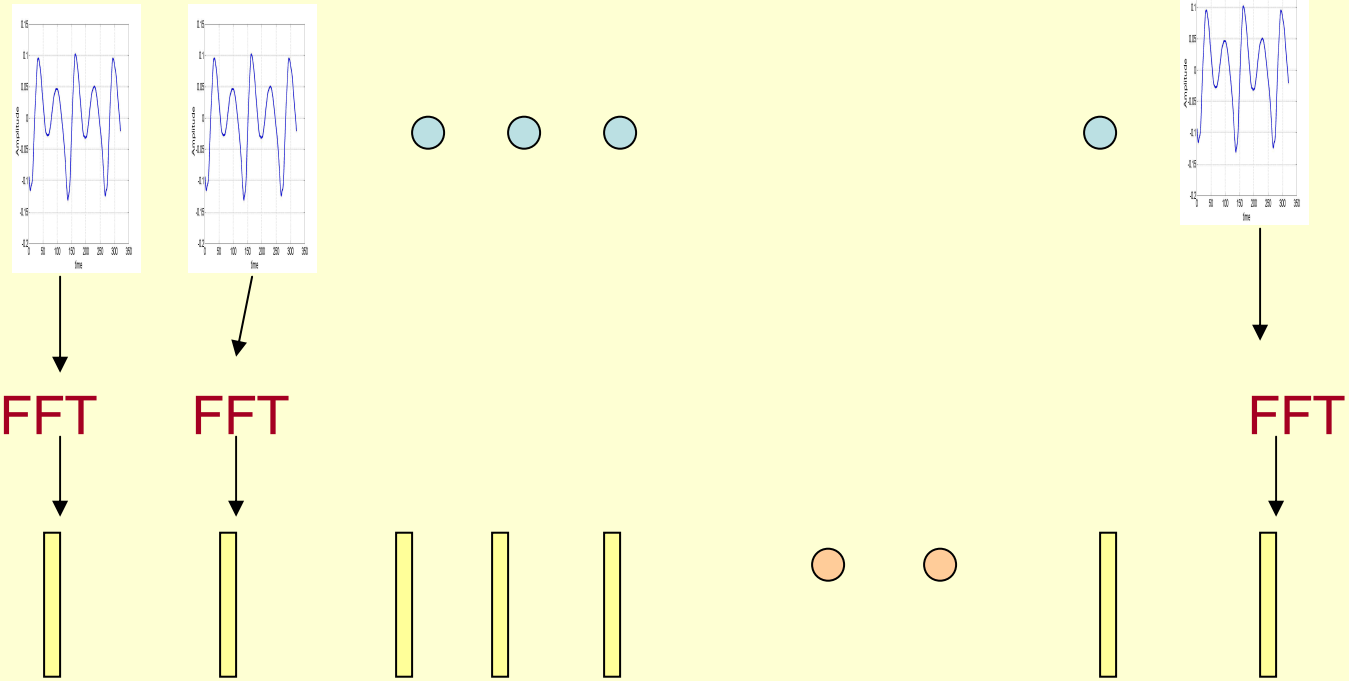
Topics

- Spectrogram
- Cepstrum
- Mel-Frequency Analysis
- Mel-Frequency Cepstral Coefficients

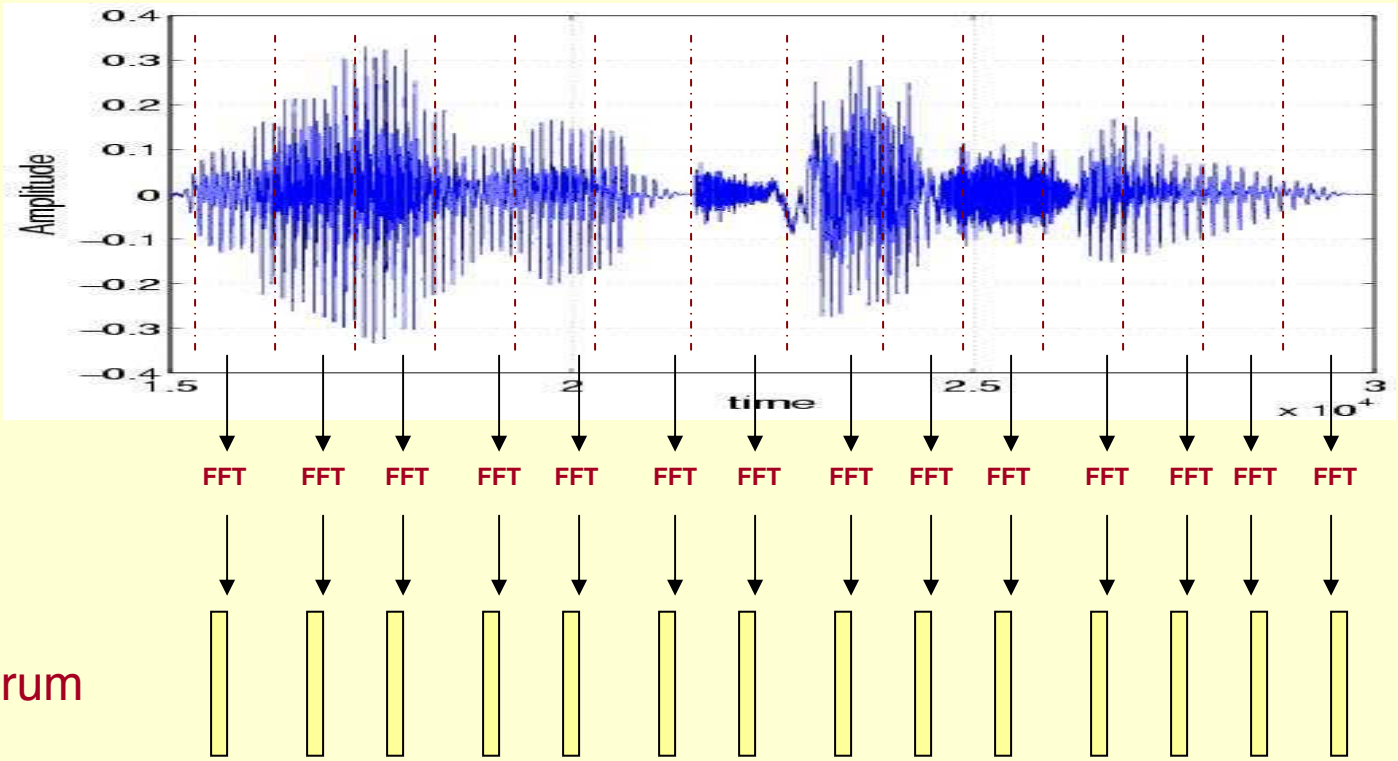
Spectrogram

Speech signal represented as a sequence of spectral vectors

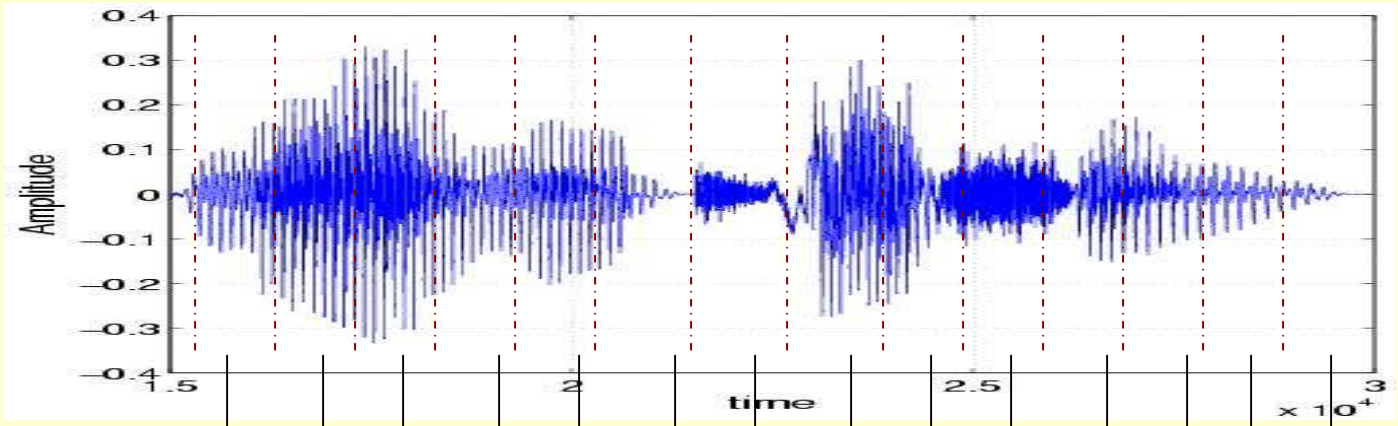


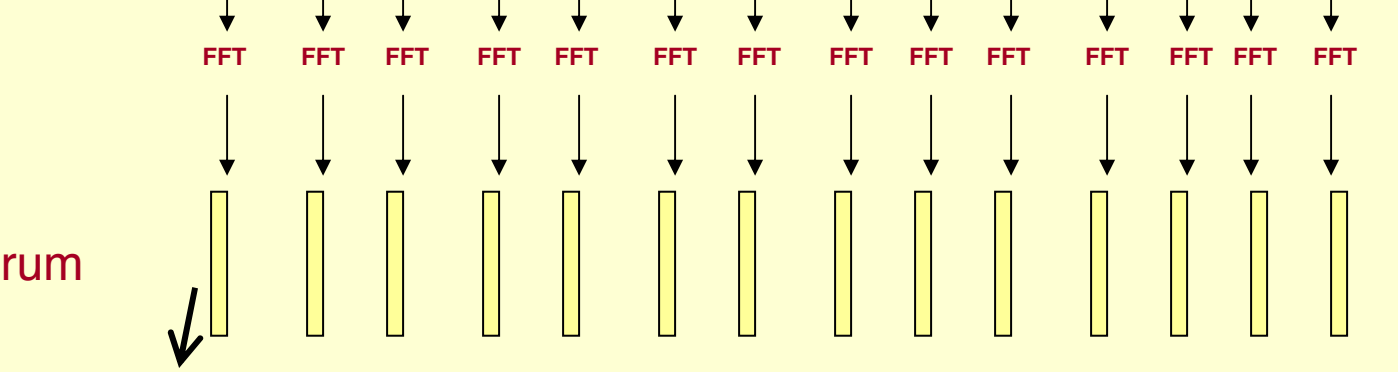


Speech signal represented as a sequence of spectral vectors

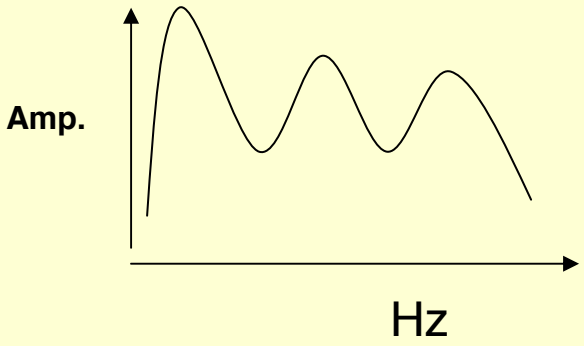


Speech signal represented as a sequence of spectral vectors

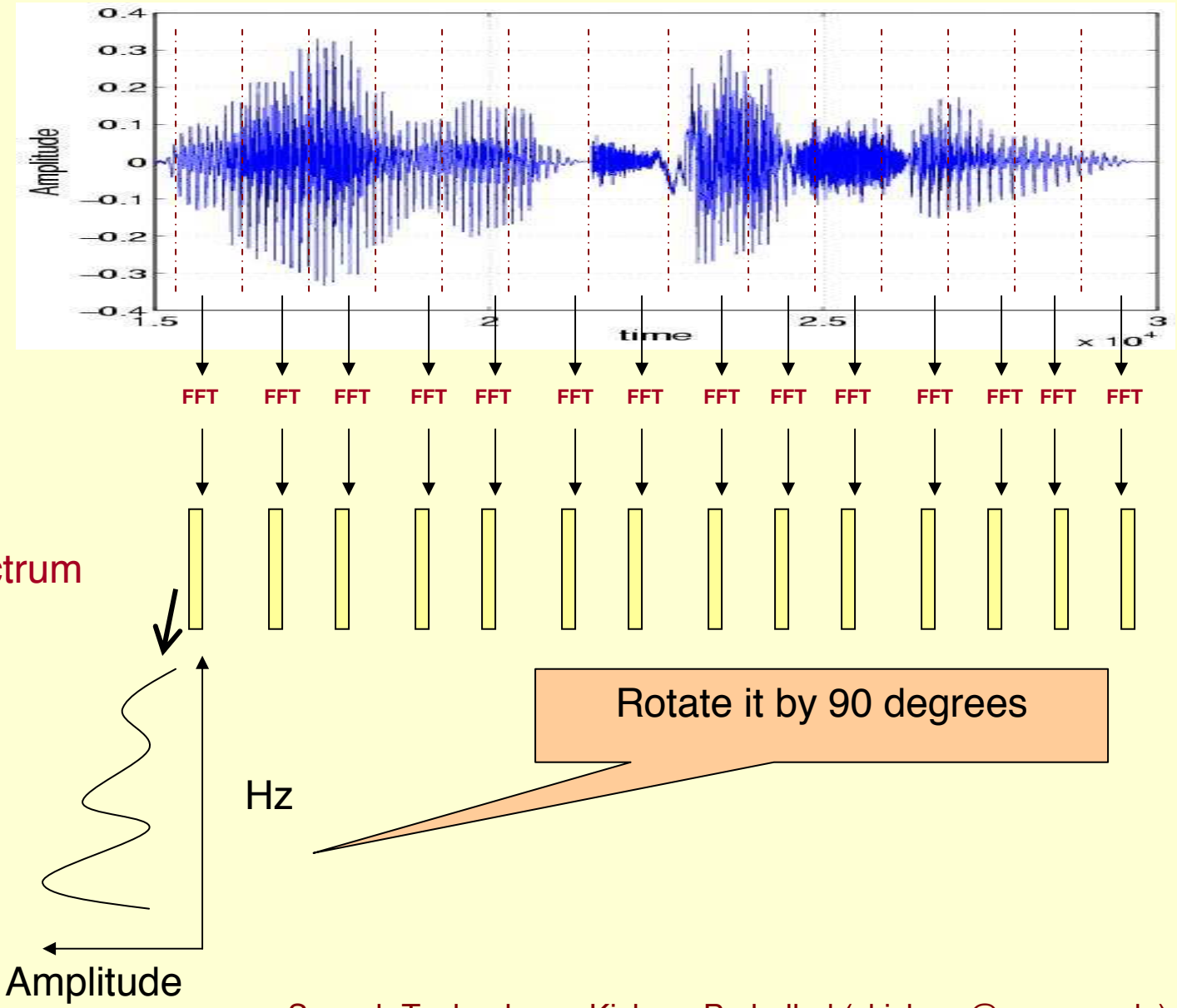




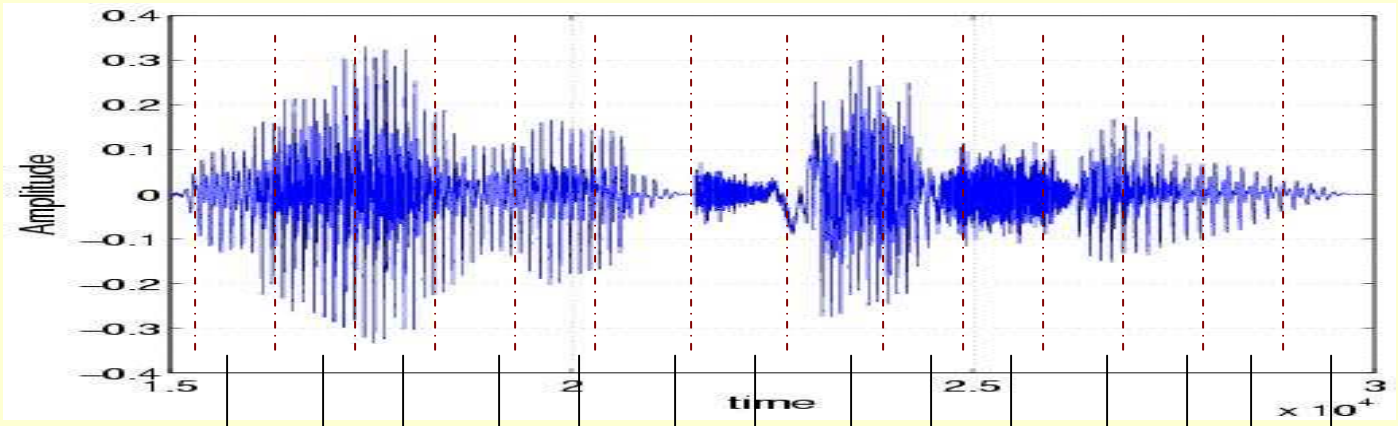
Spectrum

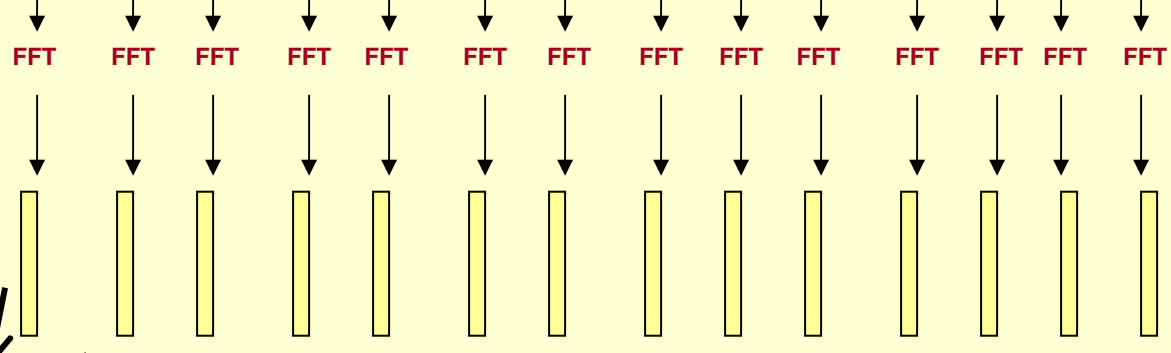


Speech signal represented as a sequence of spectral vectors

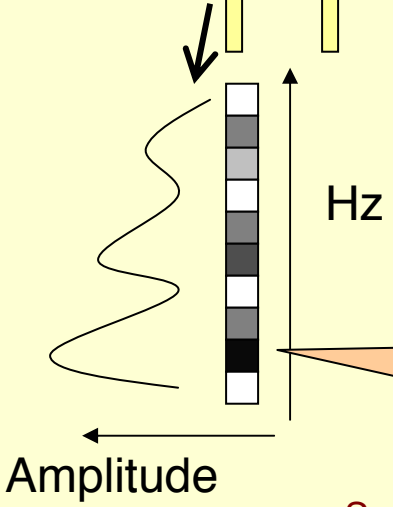


Speech signal represented as a sequence of spectral vectors



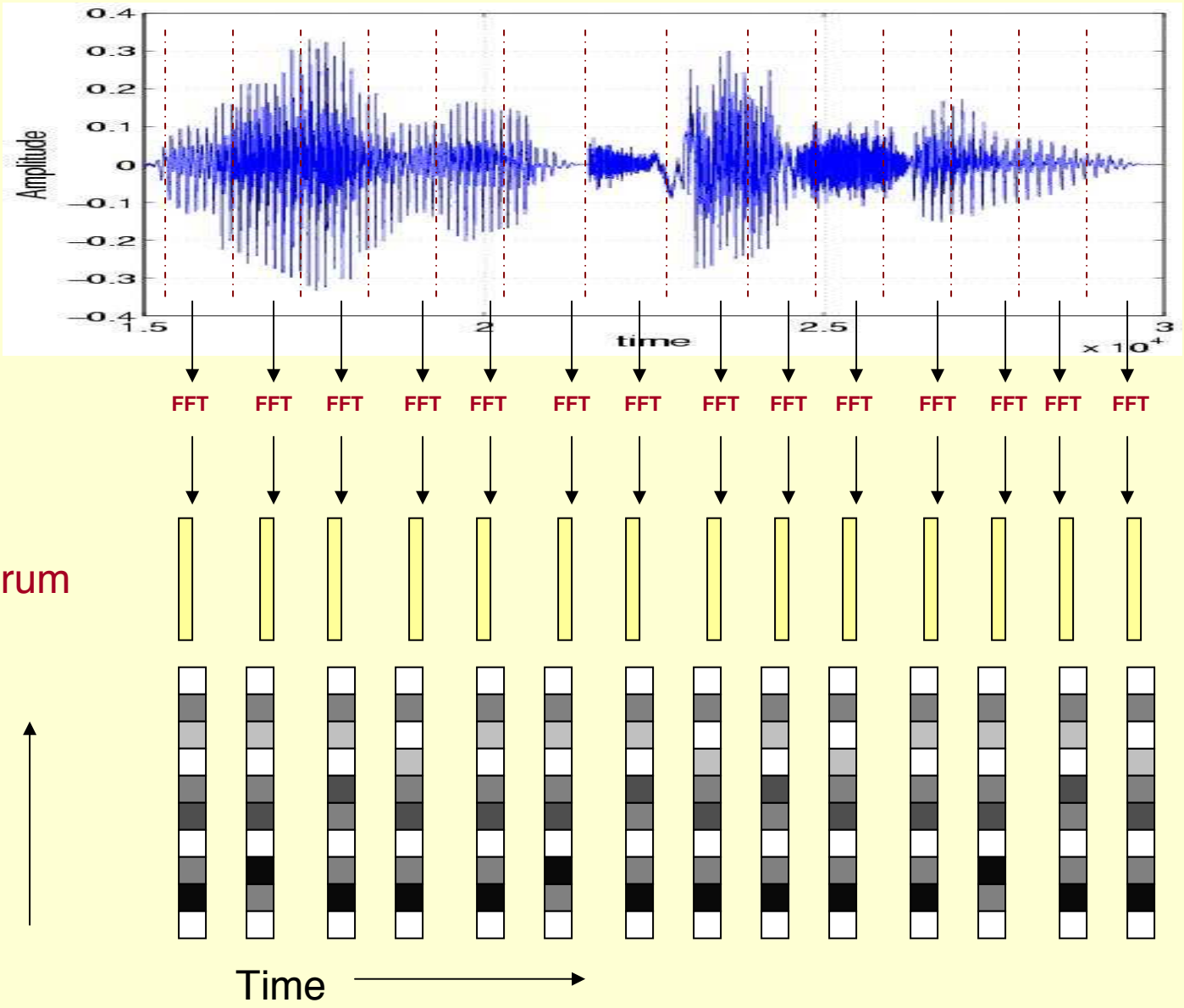


Spectrum

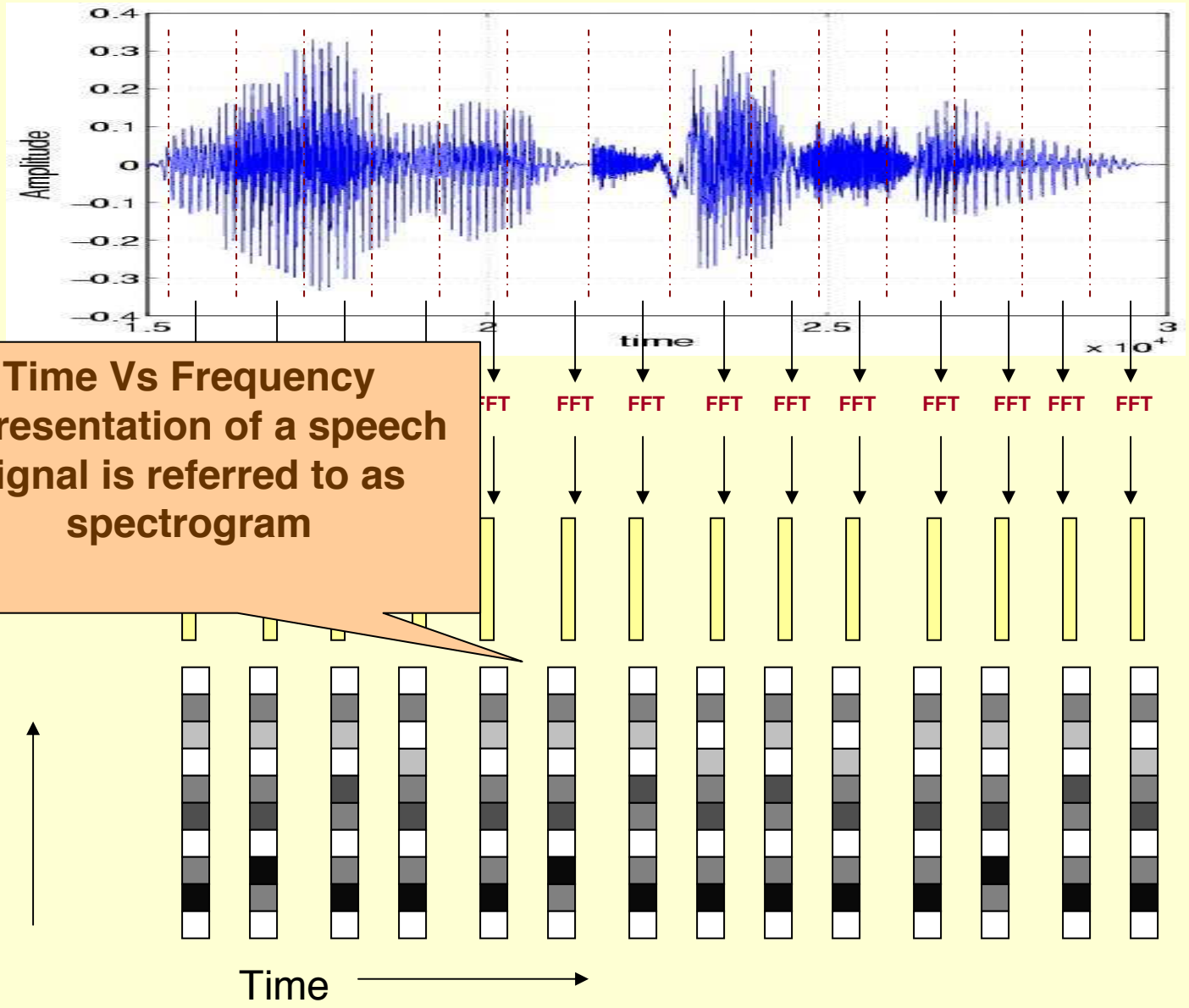


- MAP spectral amplitude to a grey level (0-255) value. 0 represents black and 255 represents white.
- Higher the amplitude, darker the corresponding region.

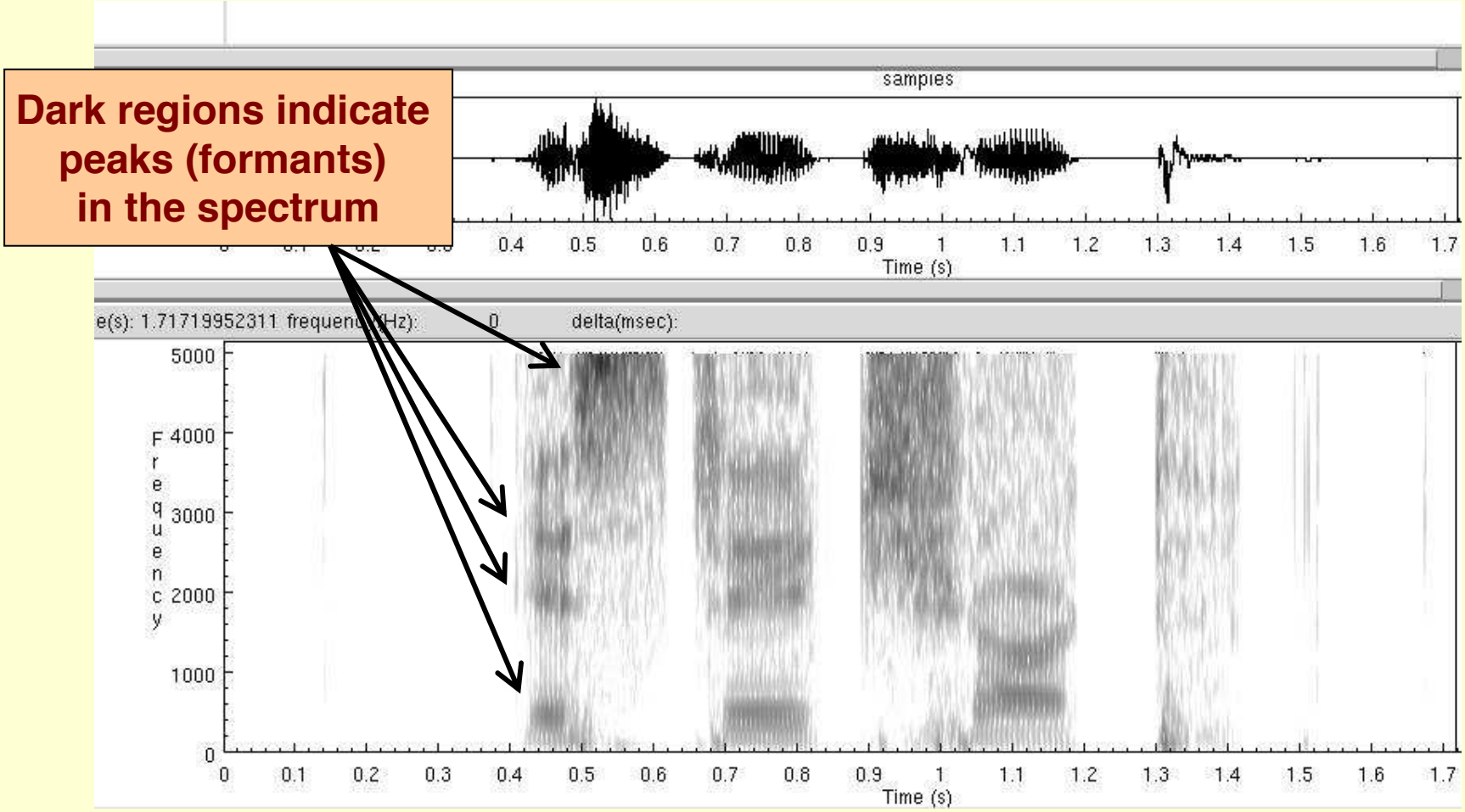
Speech signal represented as a sequence of spectral vectors



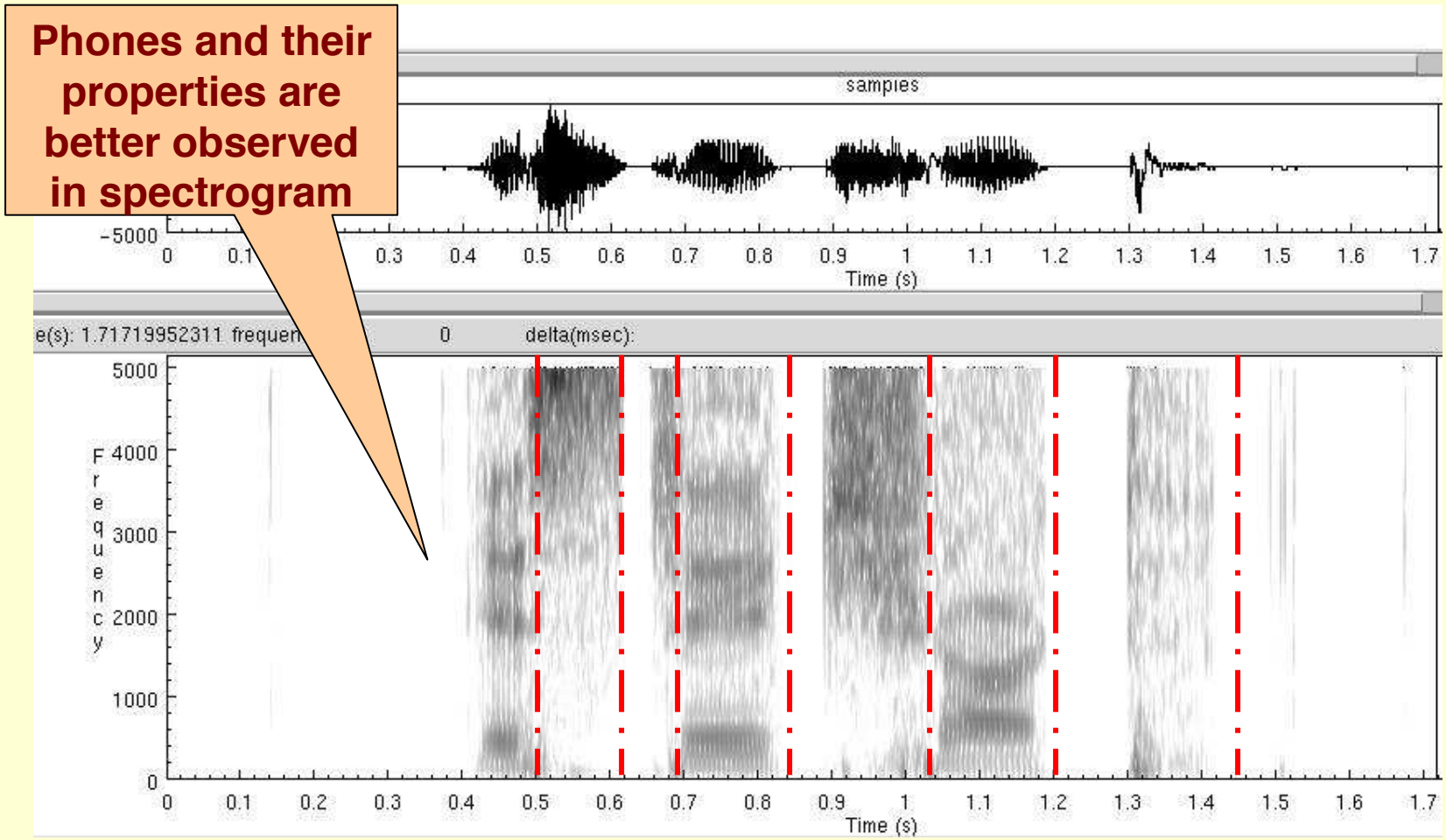
Speech signal represented as a sequence of spectral vectors



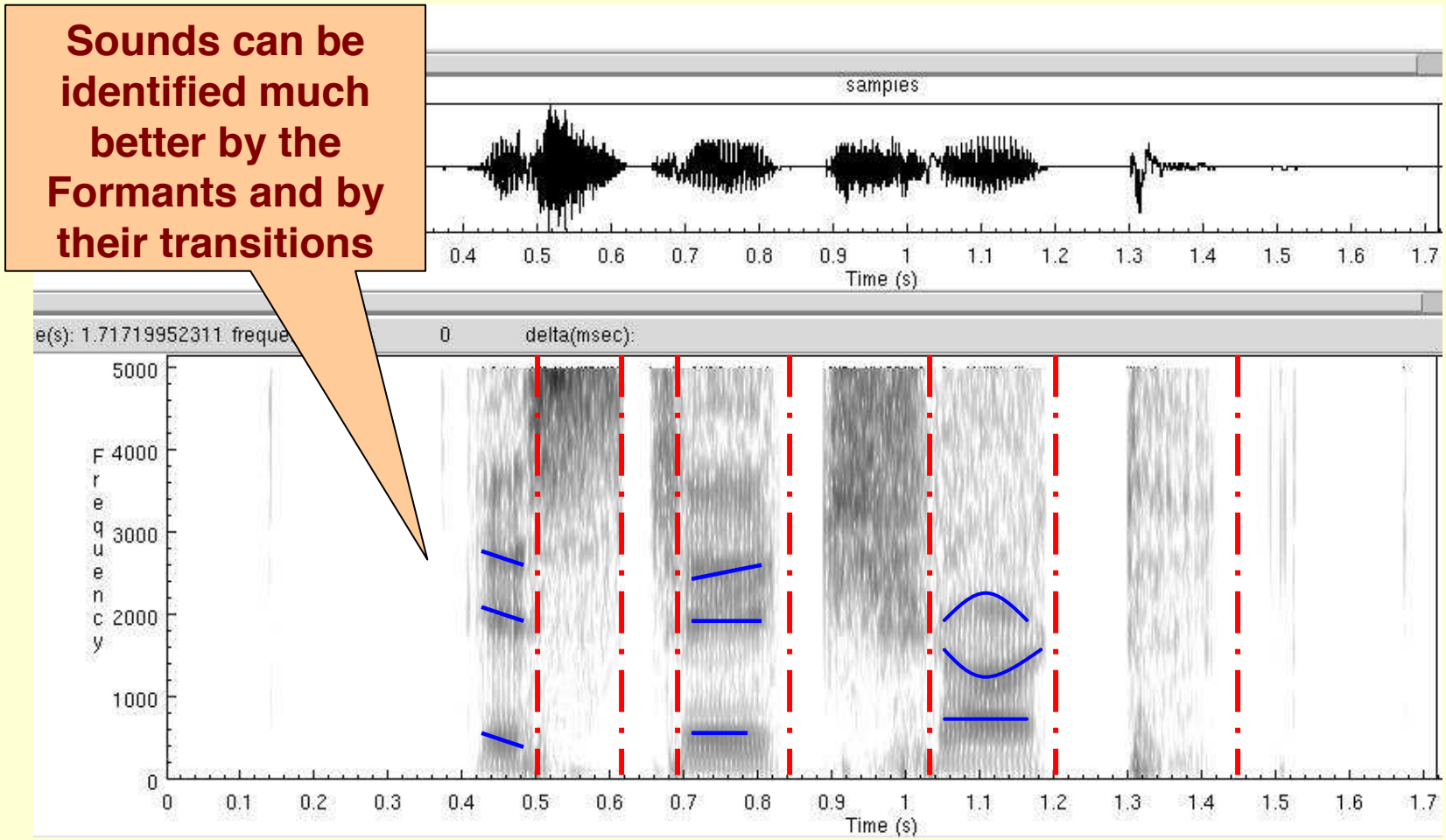
Some Real Spectrograms



Why we are bothered about spectrograms

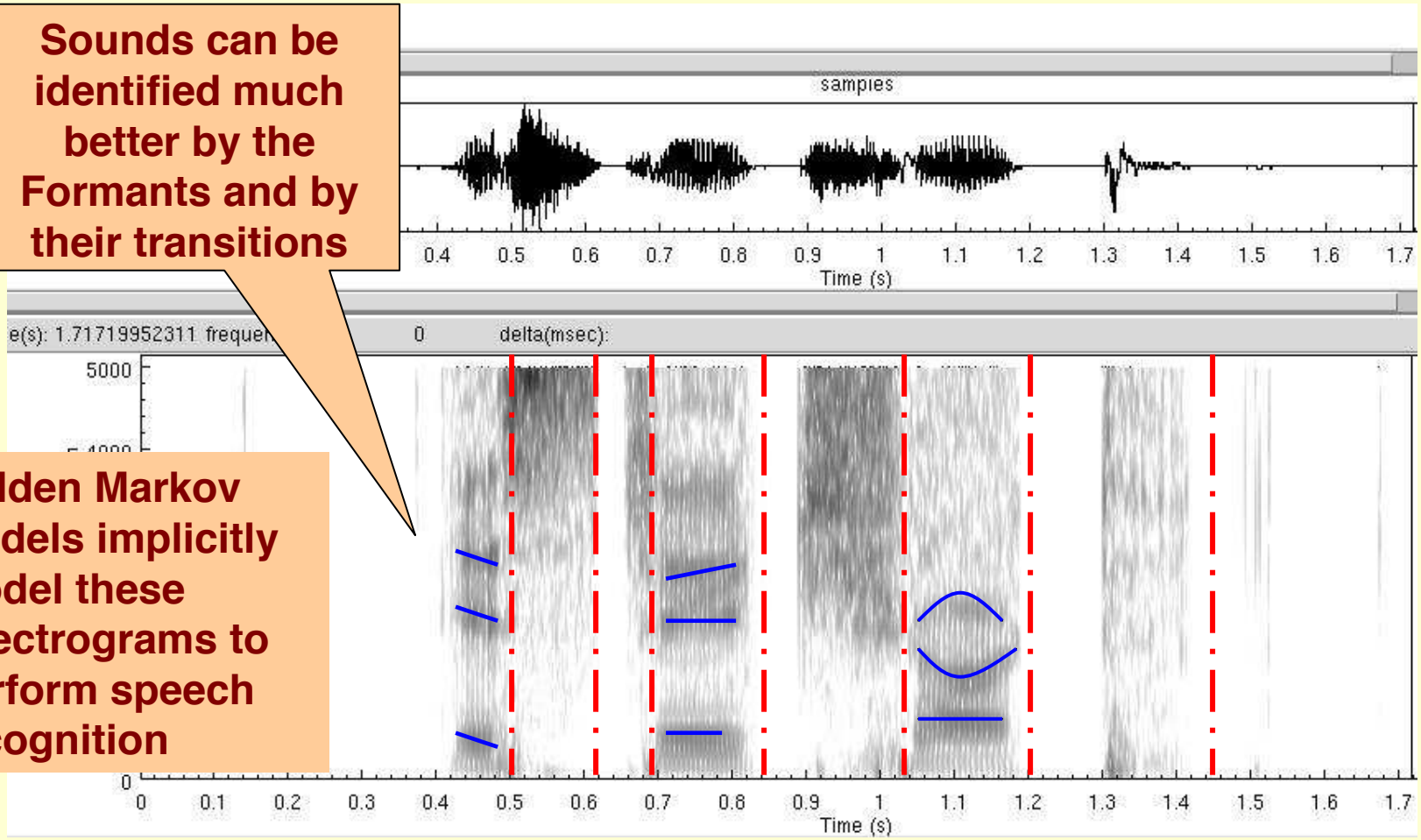


Why we are bothered about spectrograms



Why we are bothered about spectrograms

Sounds can be identified much better by the Formants and by their transitions



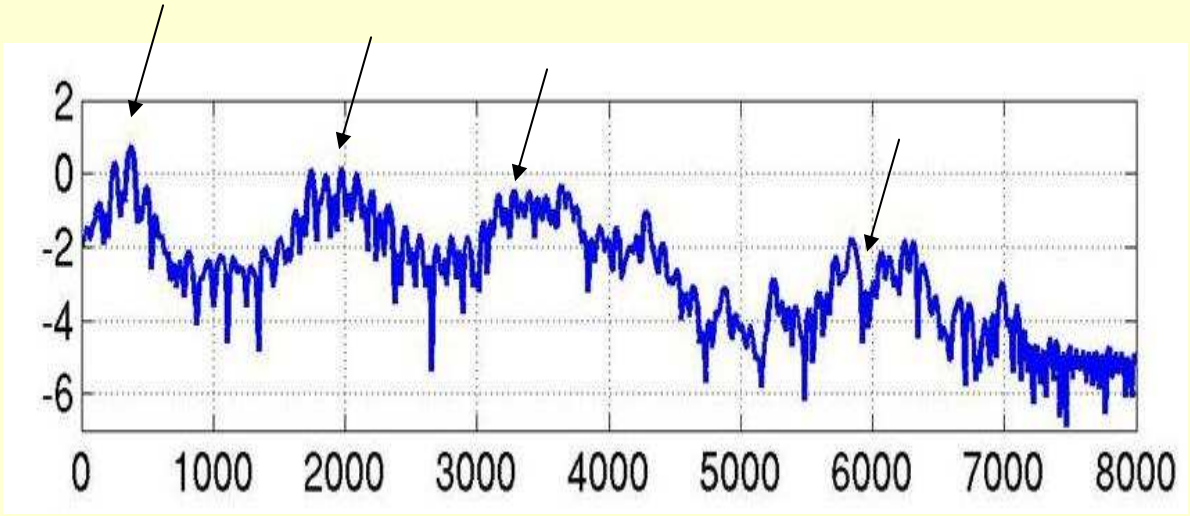
Hidden Markov Models implicitly model these spectrograms to perform speech recognition

Usefulness of Spectrogram

- Time-Frequency representation of the speech signal
- Spectrogram is a tool to study speech sounds (phones)
- Phones and their properties are visually studied by phoneticians
- Hidden Markov Models implicitly model spectrograms for speech to text systems
- Useful for evaluation of text to speech systems
  - A high quality text to speech system should produce synthesized speech whose spectrograms should nearly match with the natural sentences.

Cepstral Analysis

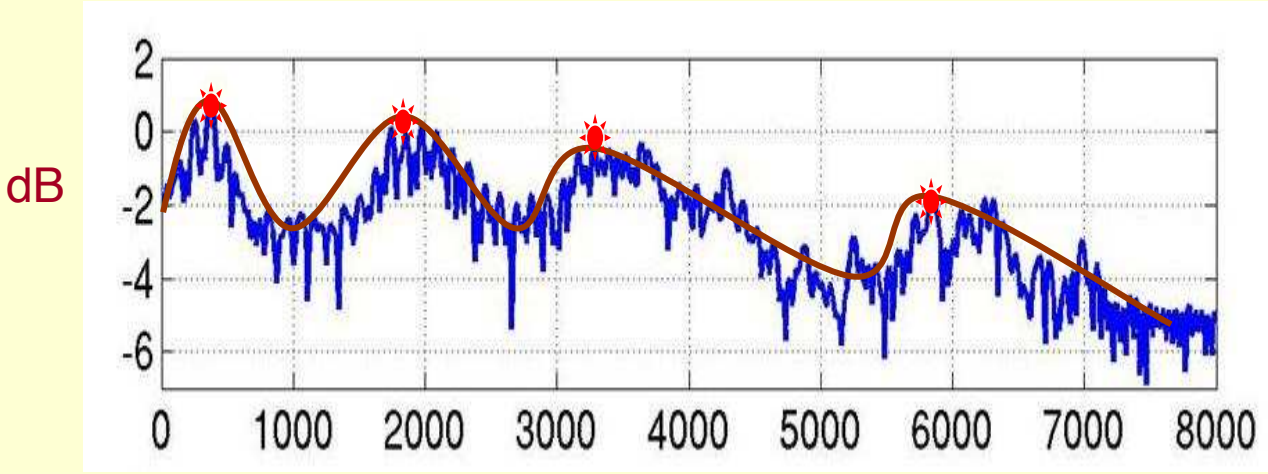
A Sample Speech Spectrum



- Peaks denote dominant frequency components in the speech signal
- Peaks are referred to as formants
- Formants carry the identity of the sound

What we want to Extract? – Spectral Envelope

- Formants and a smooth curve connecting them
- This Smooth curve is referred to as spectral envelope

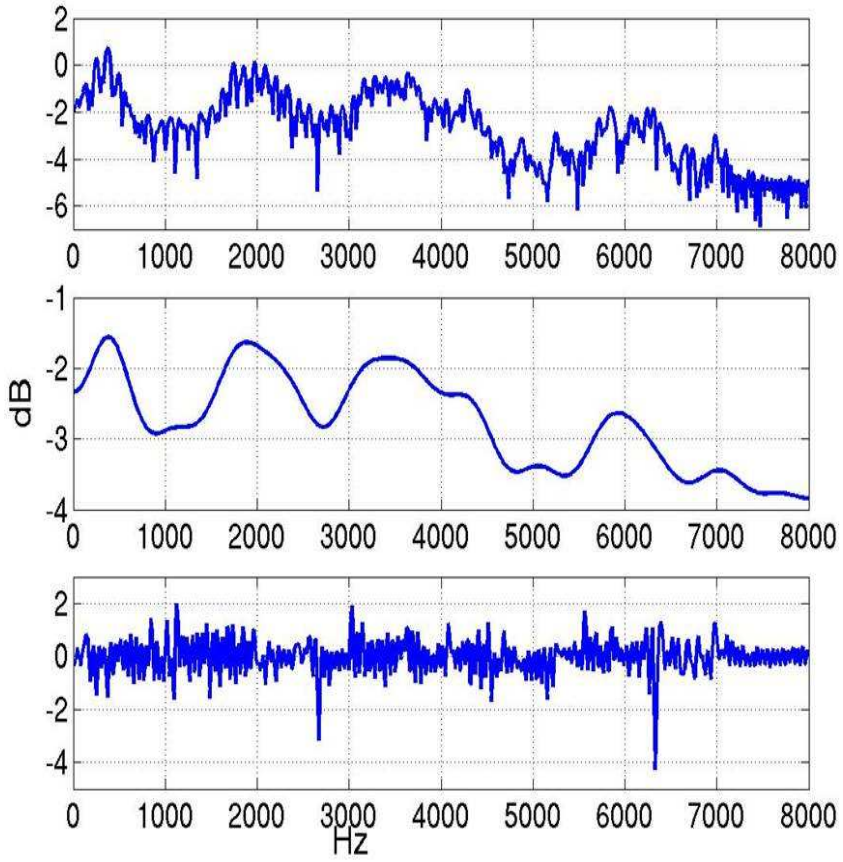


Spectral Envelope

Spectrum

Spectral Envelope

Spectral details

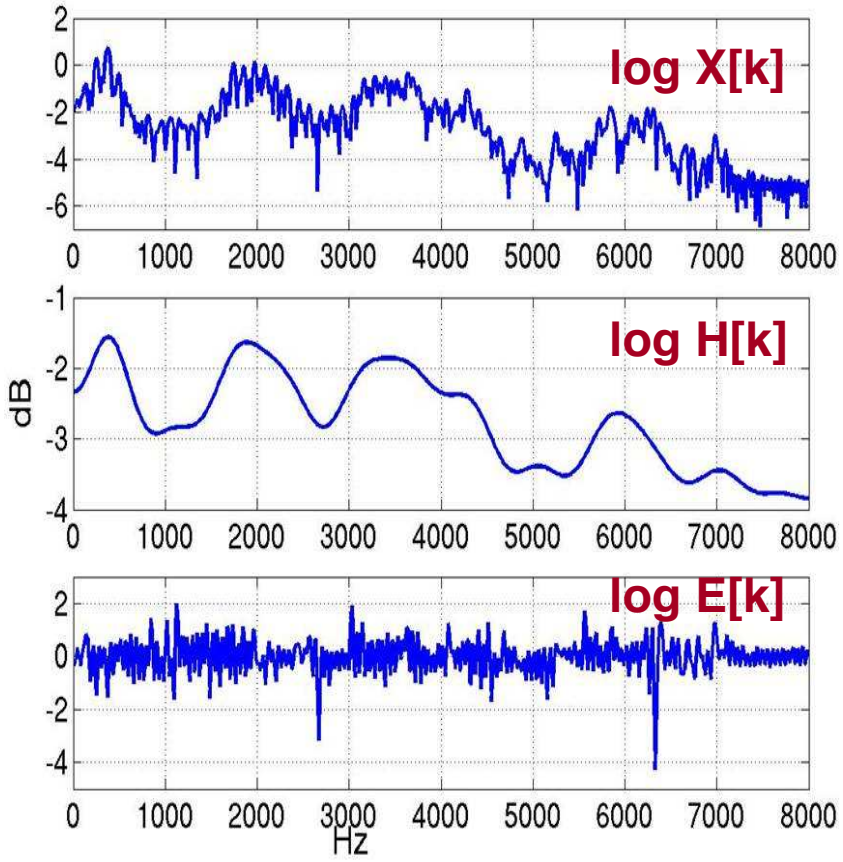


Spectral Envelope

Spectrum

Spectral Envelope

Spectral details

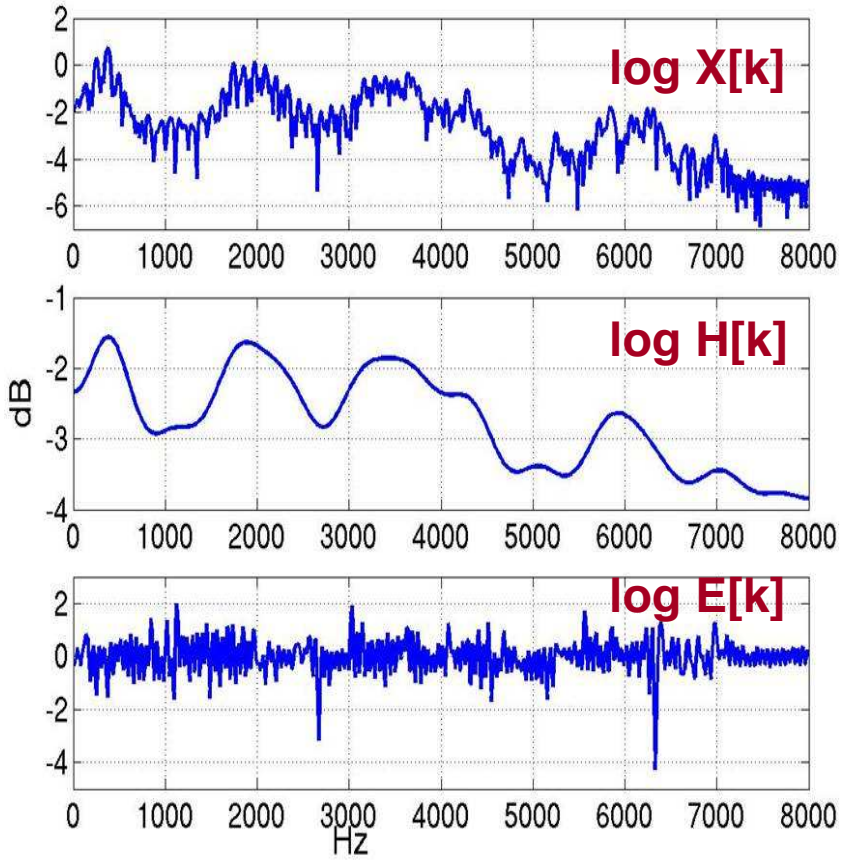


Spectral Envelope

Spectrum

Spectral Envelope

Spectral details



log X[k] = log H[k] + log E[k]

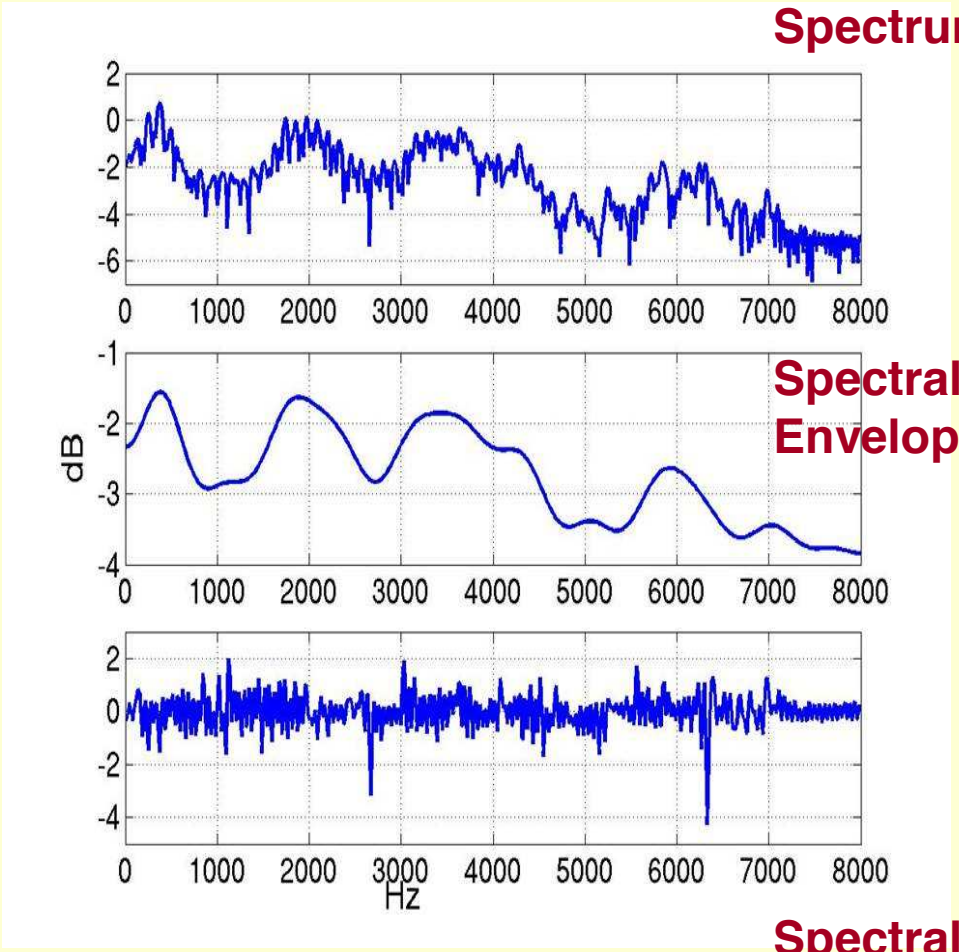
1. Our goal: We want to separate spectral envelope and spectral details from the spectrum.

2. i.e Given log X[k], obtain log H[k] and log E[k], such that log X[k] = log H[k] + log E[k]

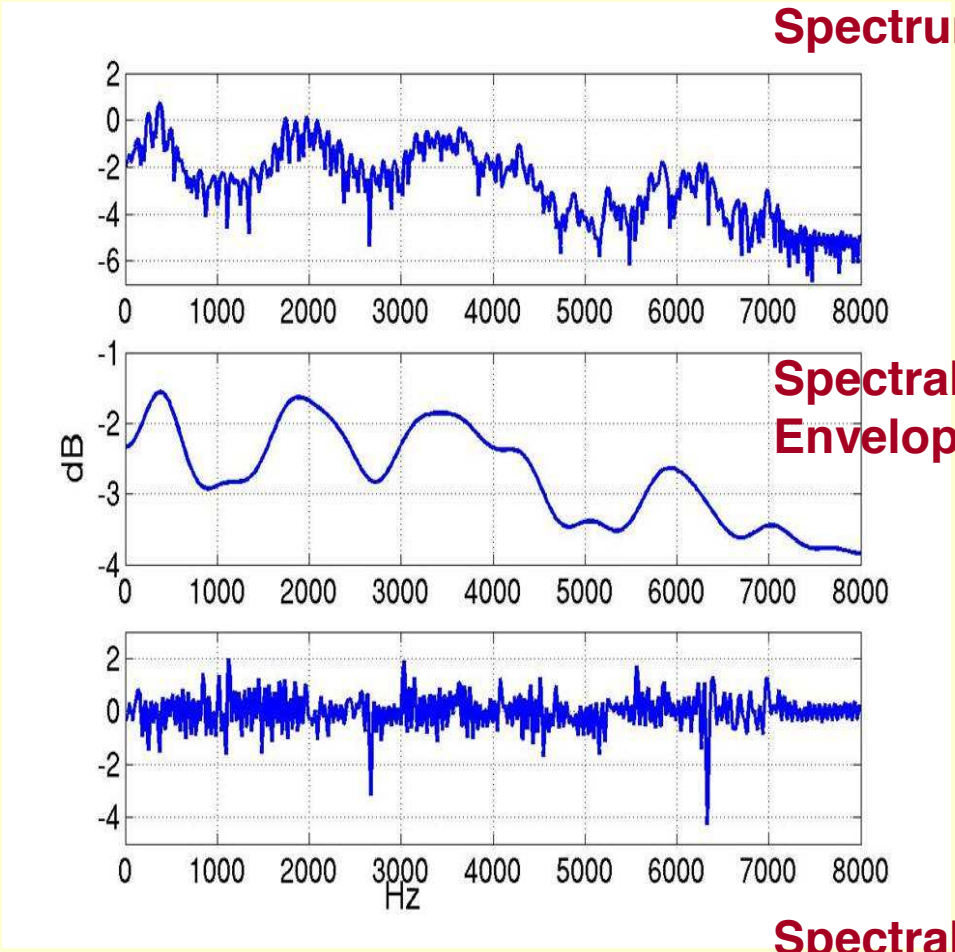
How to achieve this separation ?

Play a Mathematical Trick

- **Trick: Take FFT of the spectrum!!**
- **An FFT on spectrum referred to as Inverse FFT (IFFT).**
- **Note: We are dealing with spectrum in log domain (part of the trick)**
- **IFFT of log spectrum would represent the signal in pseudo-frequency axis**

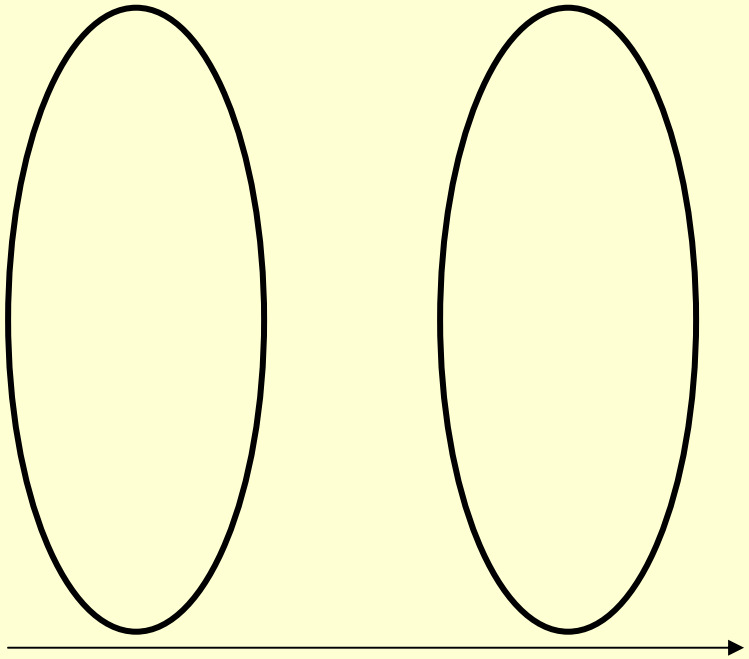


Play a Mathematical Trick

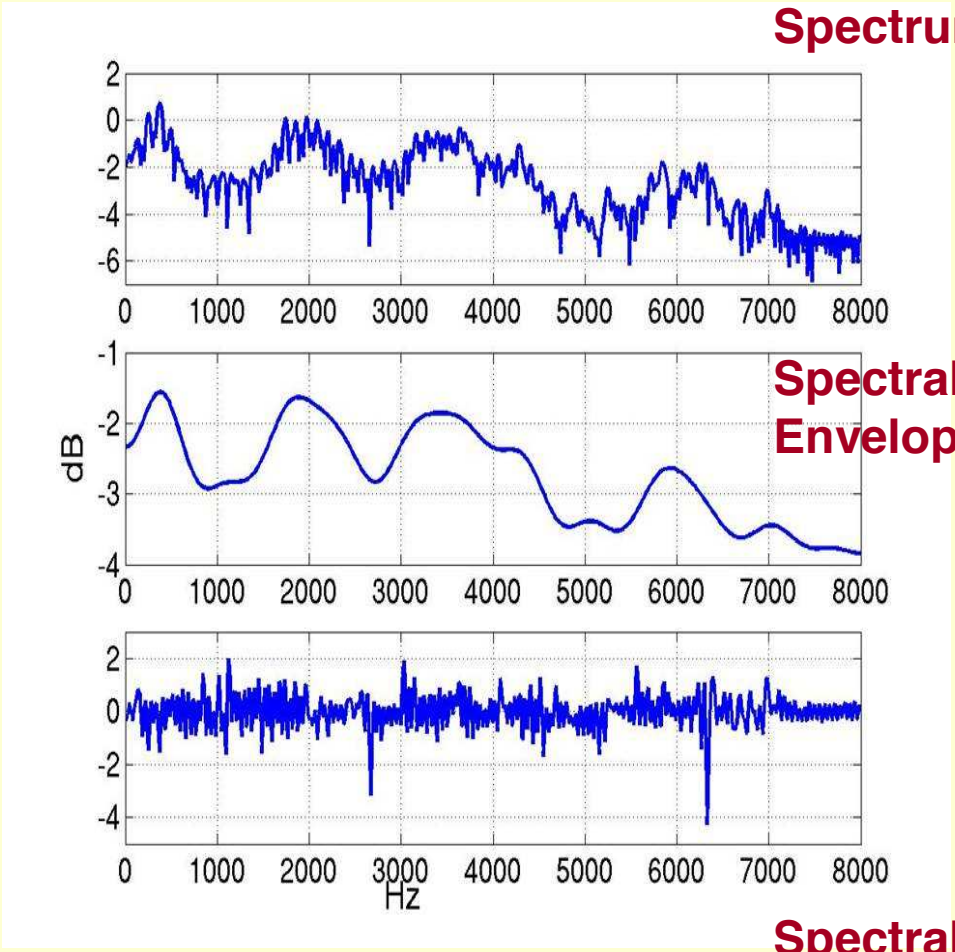


A pseudo-frequency axis

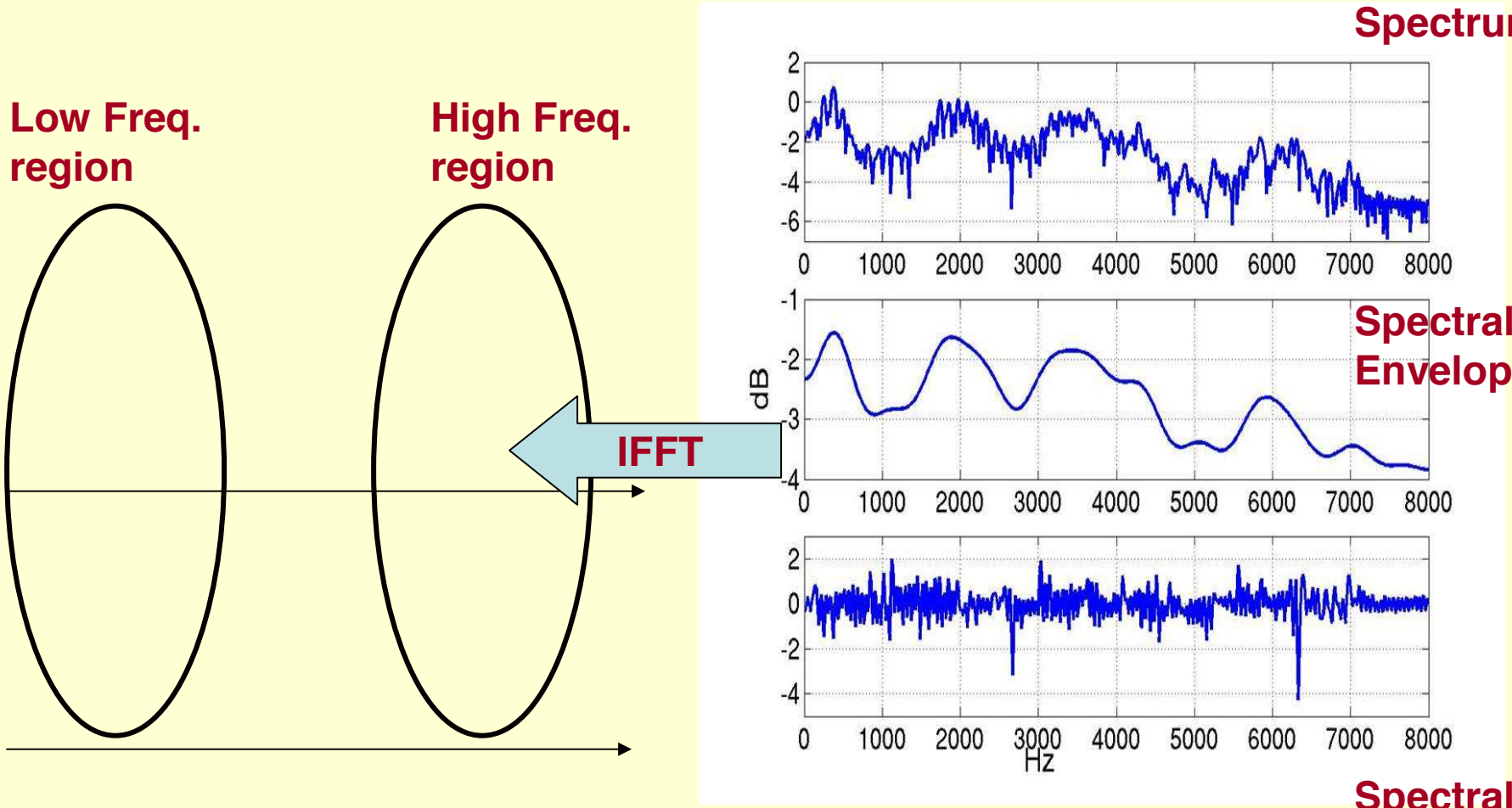
Play a Mathematical Trick



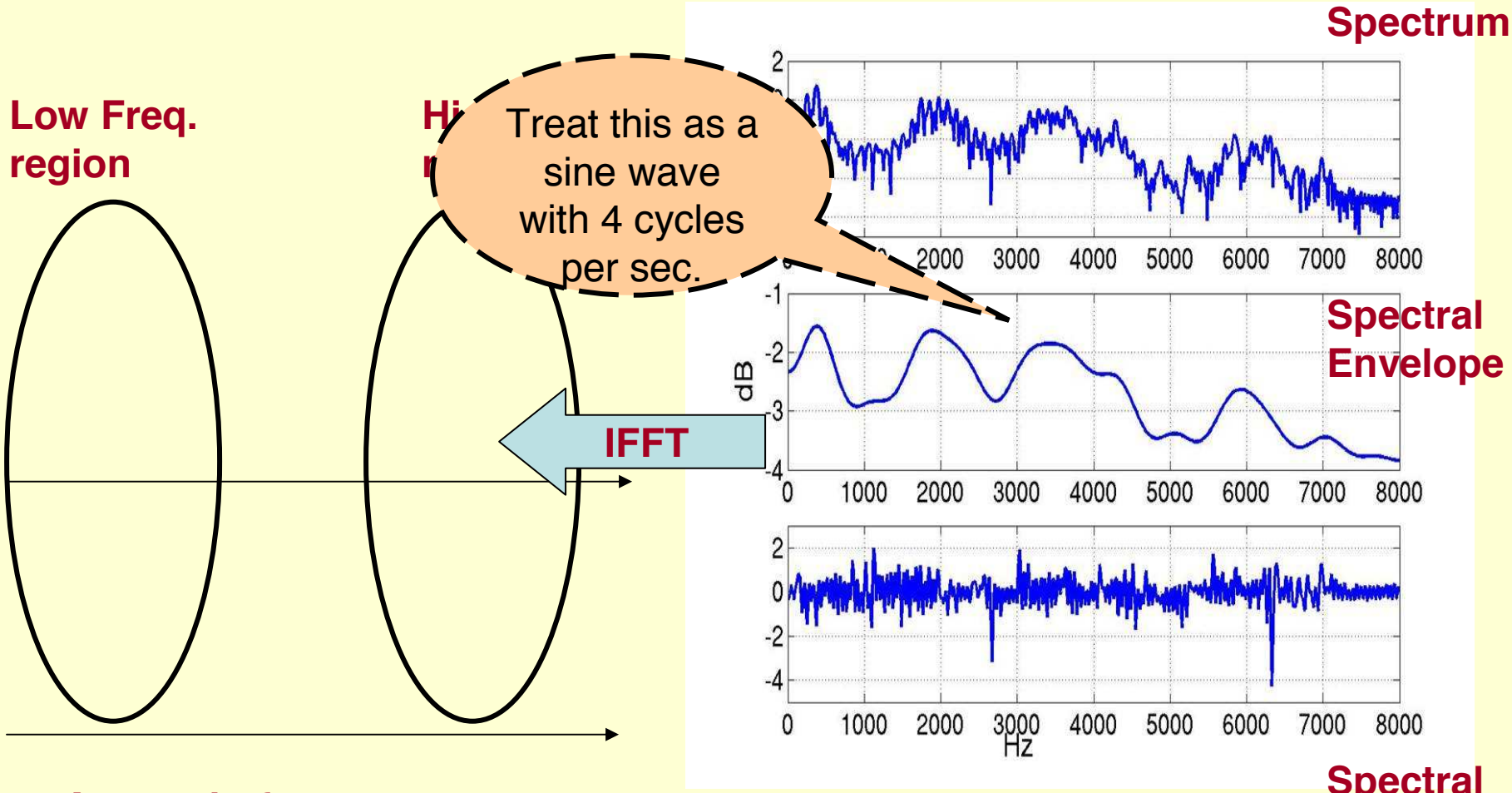
A pseudo-frequency axis



Play a Mathematical Trick



Play a Mathematical Trick



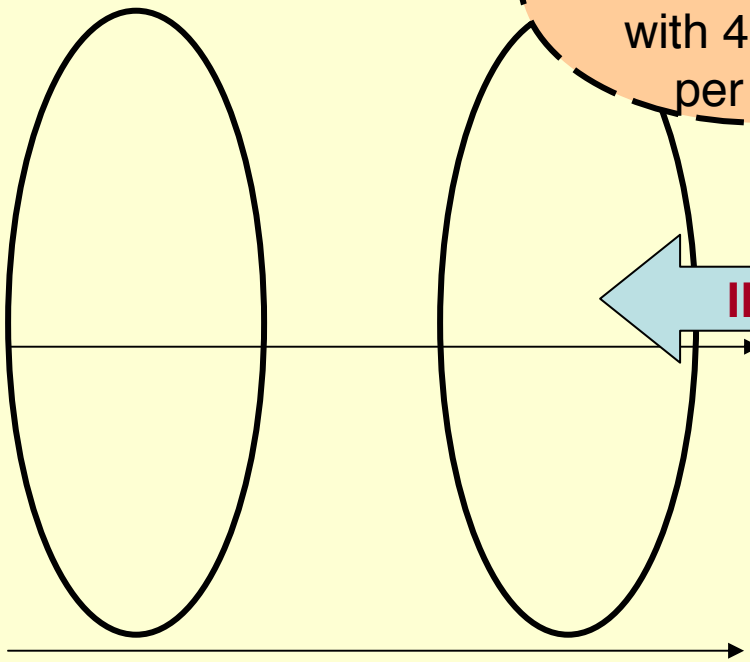
a Mathematical Trick

Gives a peak at 4 Hz in frequency axis

Treat this as a sine wave with 4 cycles per sec.

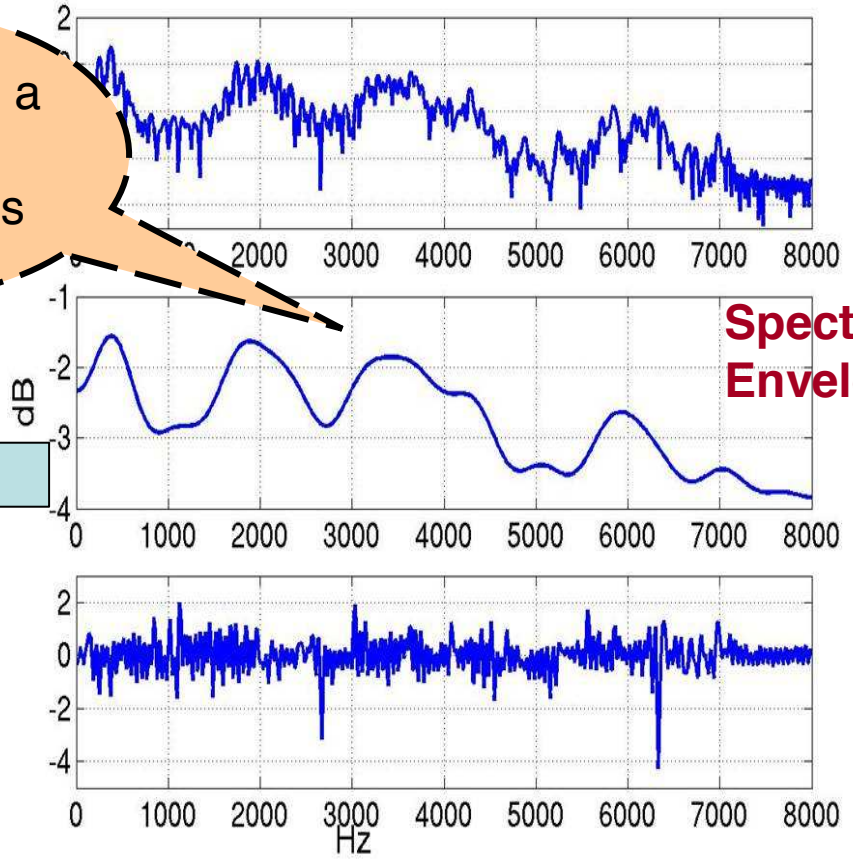
Low Freq. region

Hi



IFFT

Spectrum

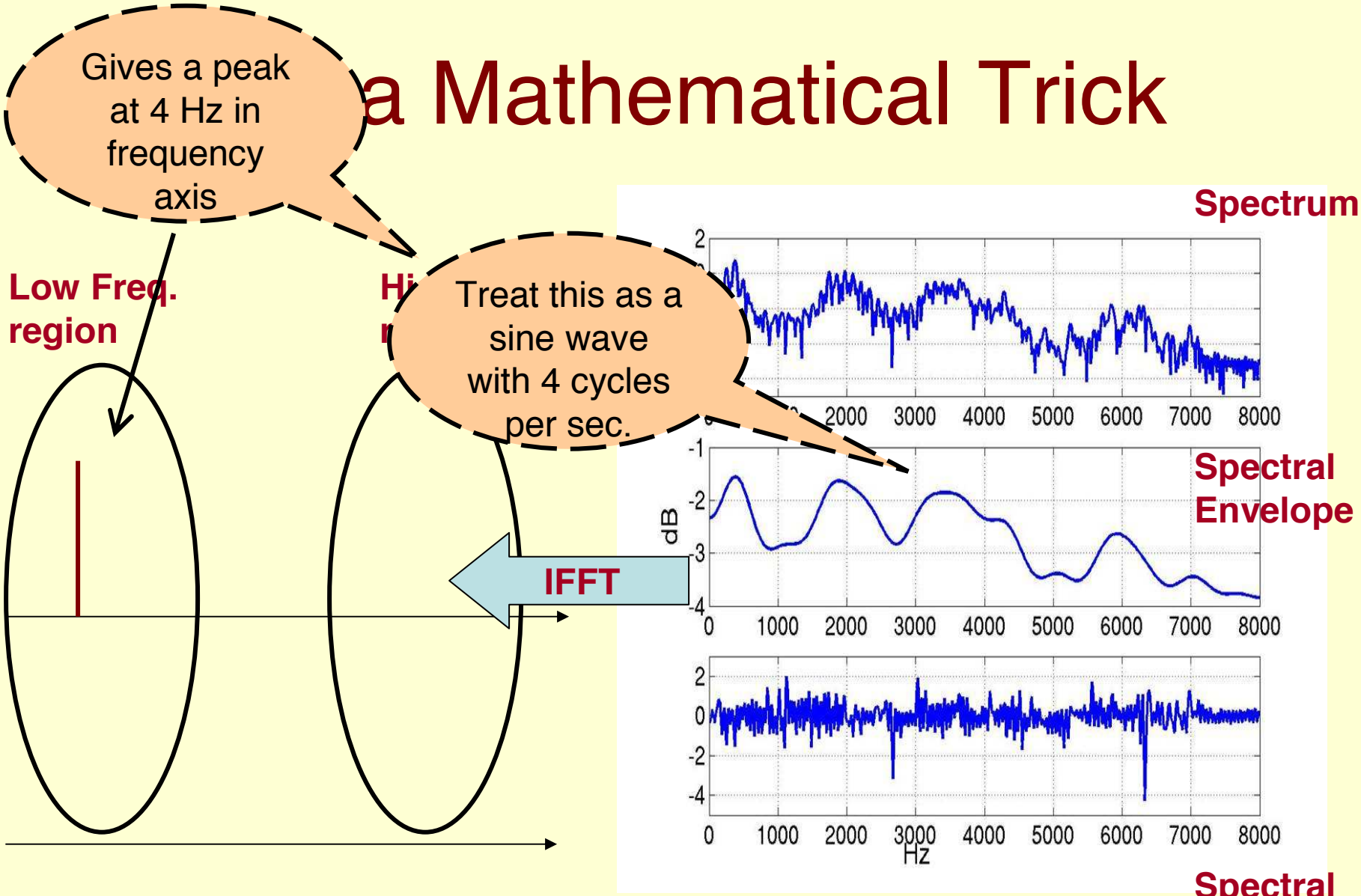


Spectral Envelope

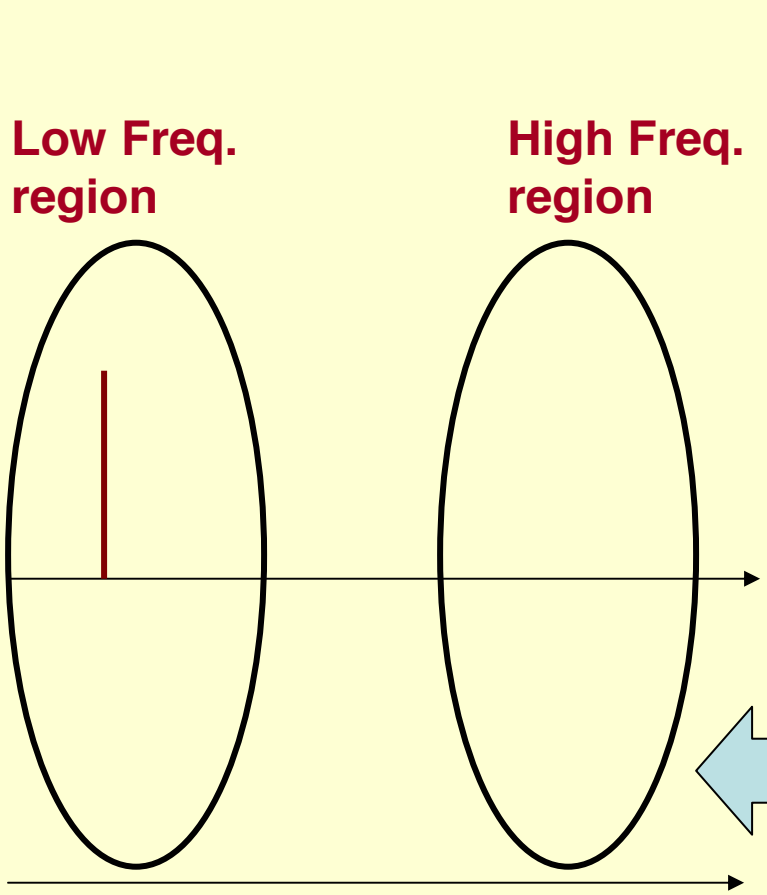
Spectral details

A pseudo-frequency axis

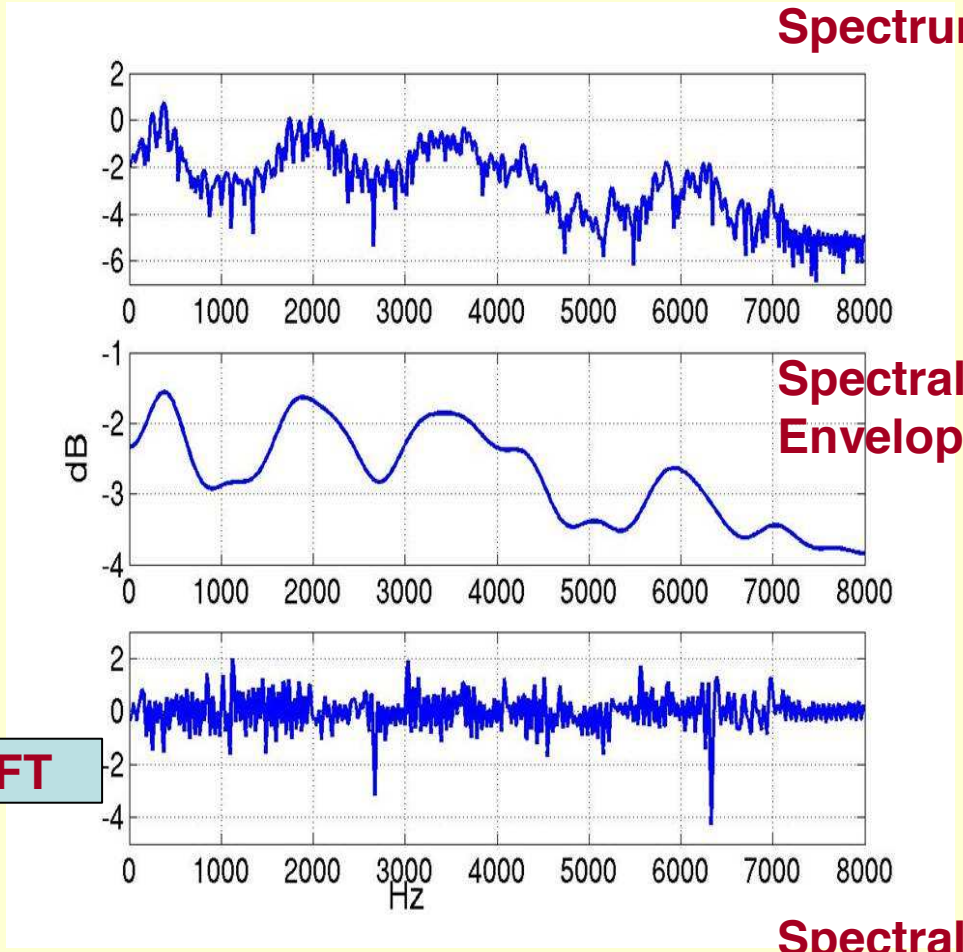
a Mathematical Trick



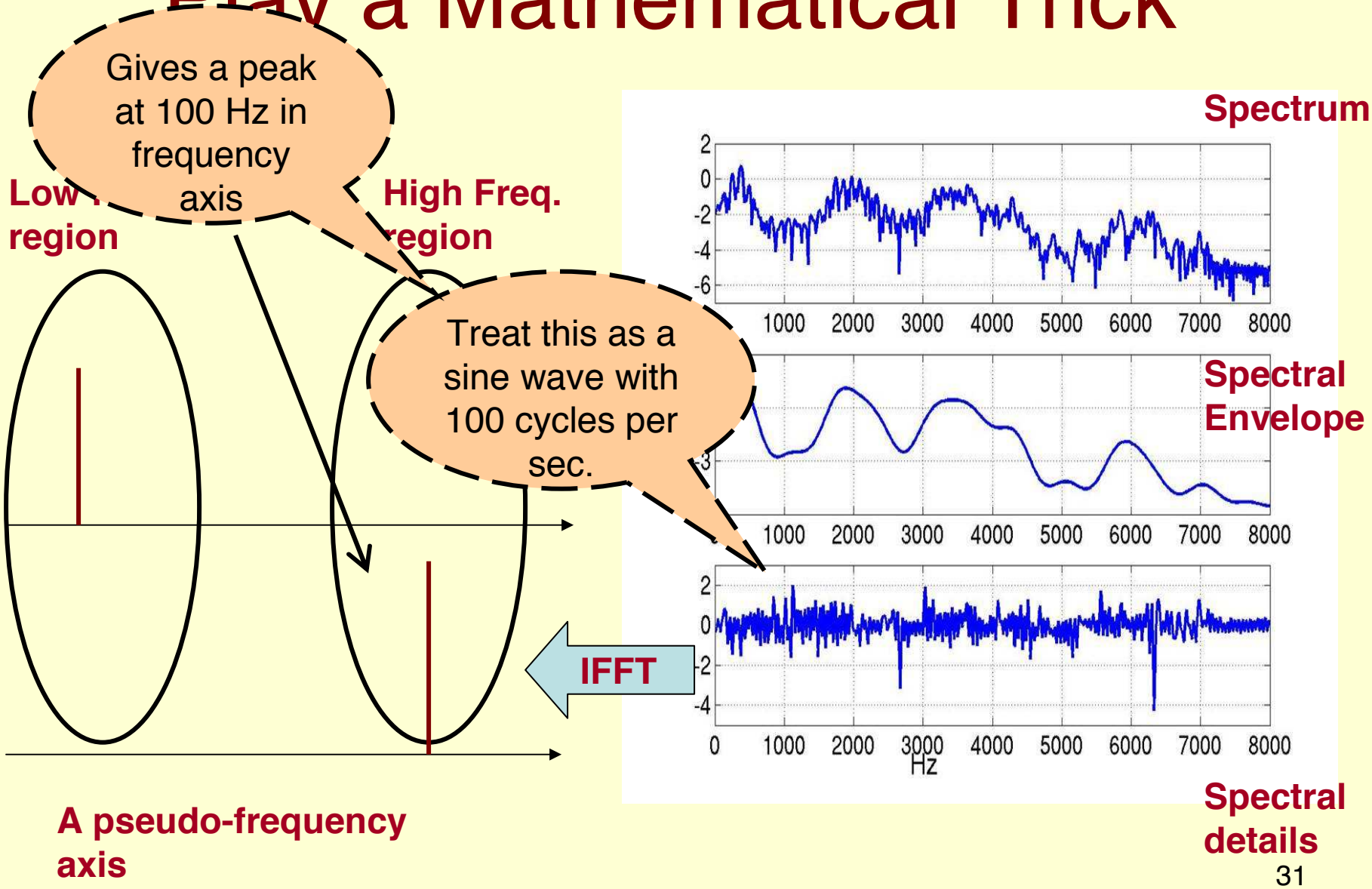
Play a Mathematical Trick



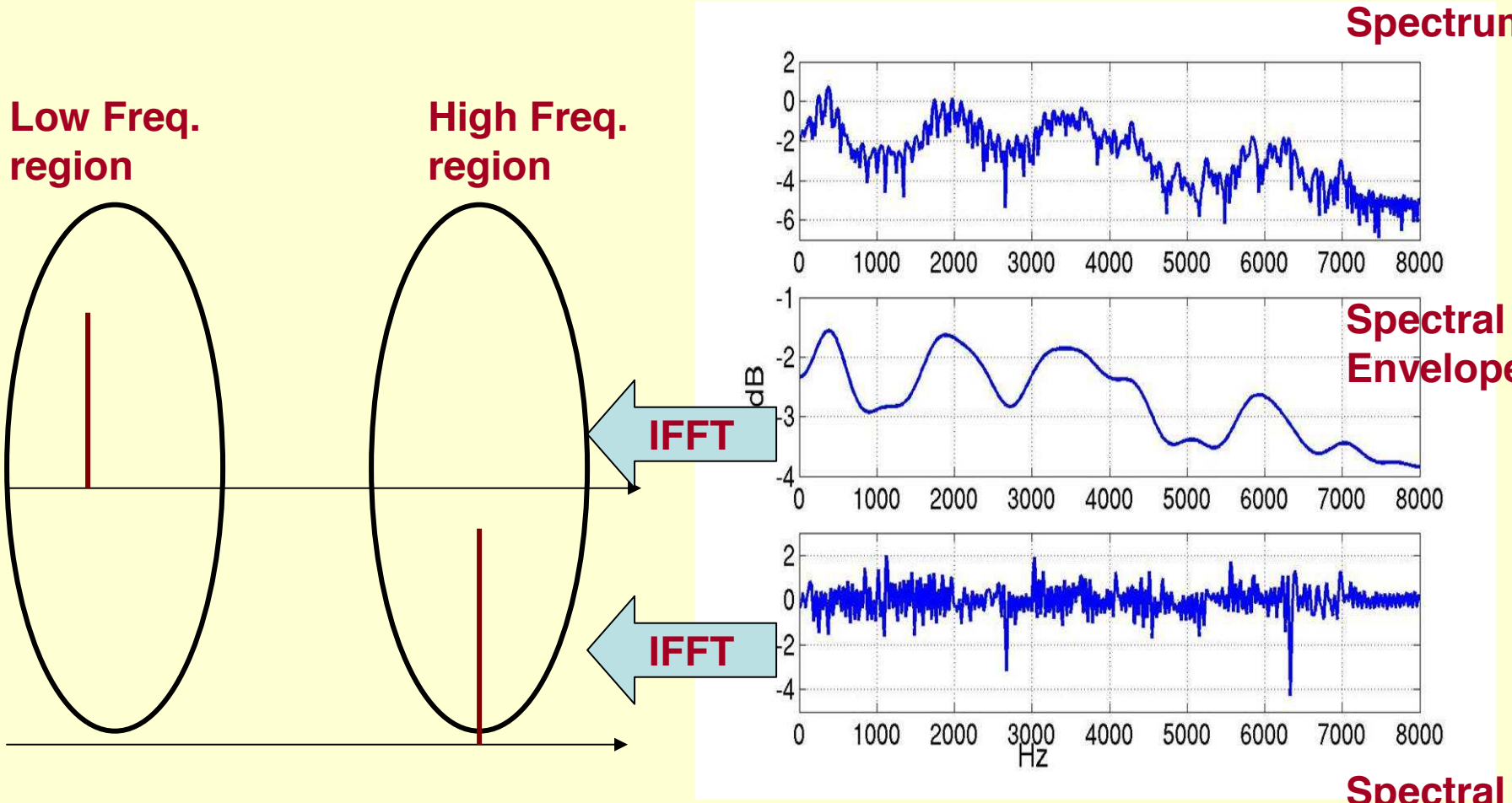
IFFT



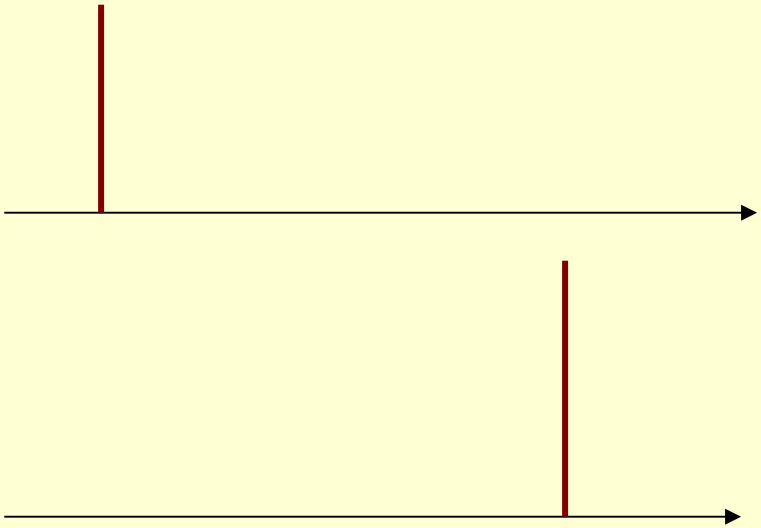
Play a Mathematical Trick



Play a Mathematical Trick

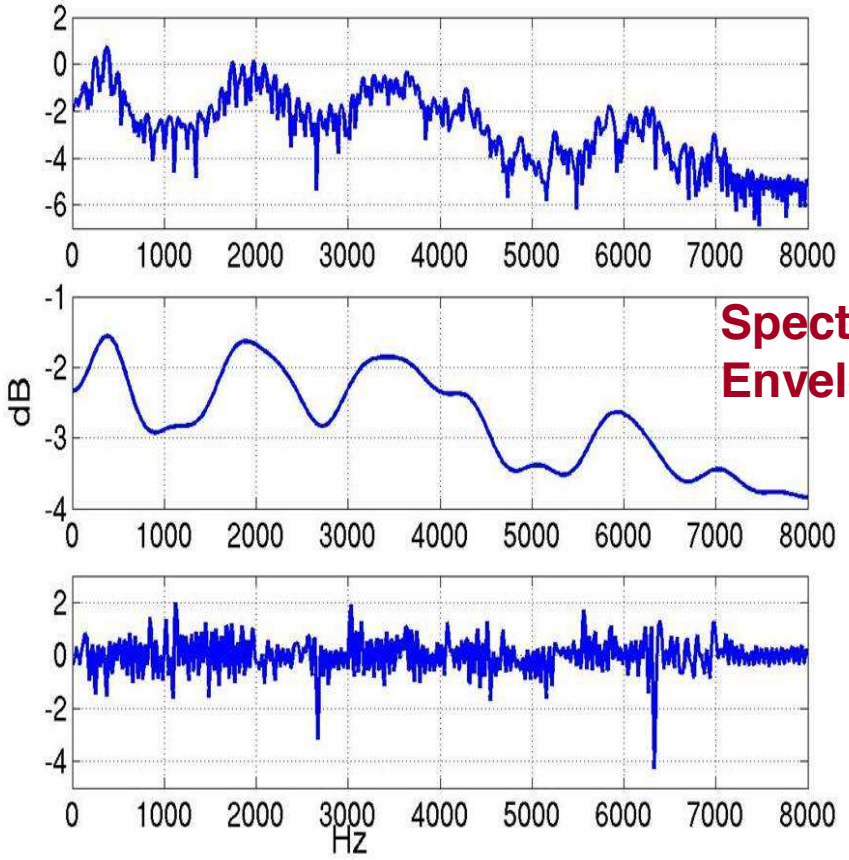


Play a Mathematical Trick



A pseudo-frequency axis

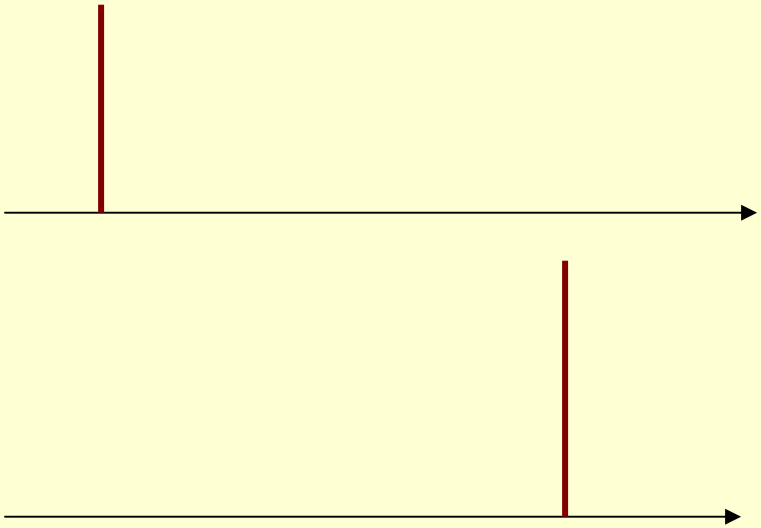
Spectrum



Spectral Envelope

Spectral details

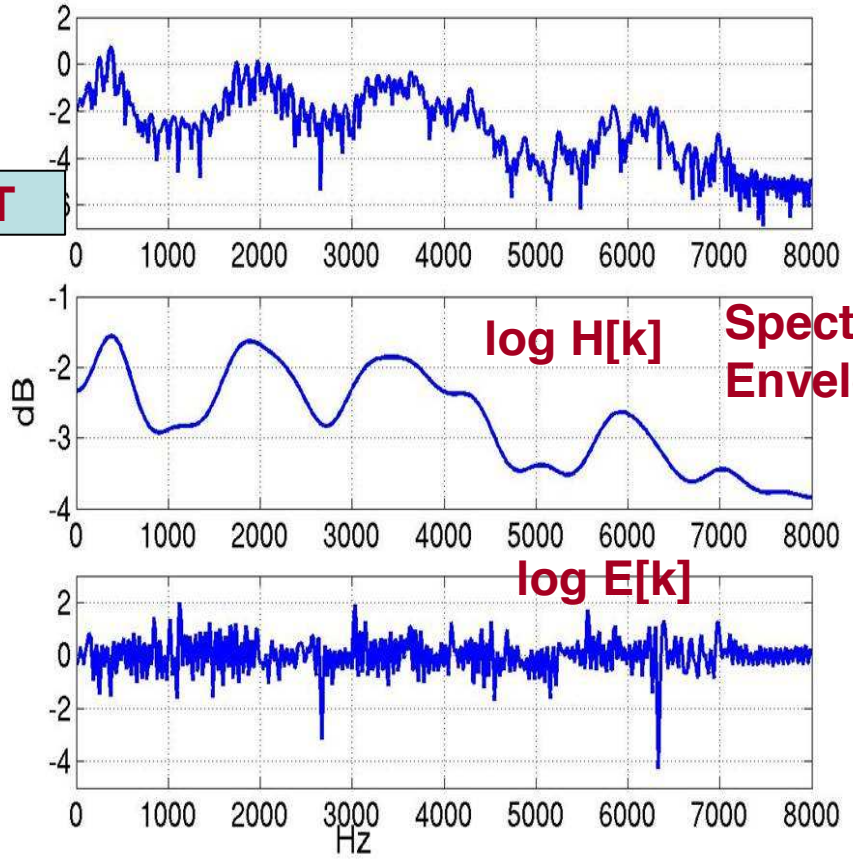
Play a Mathematical Trick



A pseudo-frequency axis

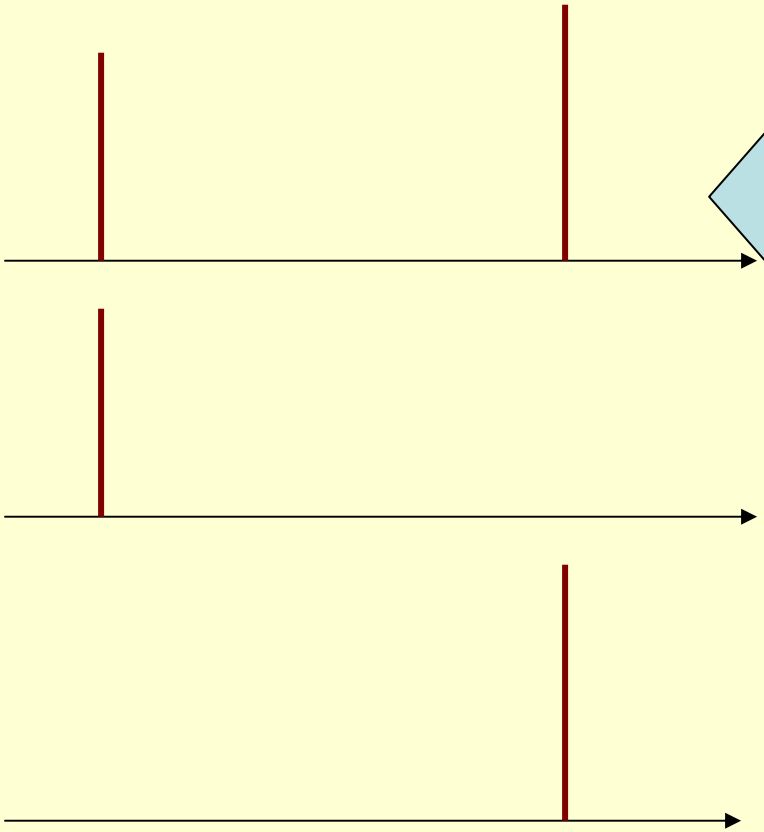
log X[k] = log H[k] + log E[k]

IFFT



Play a Mathematical Trick

x[k] = h[k] + e[k]

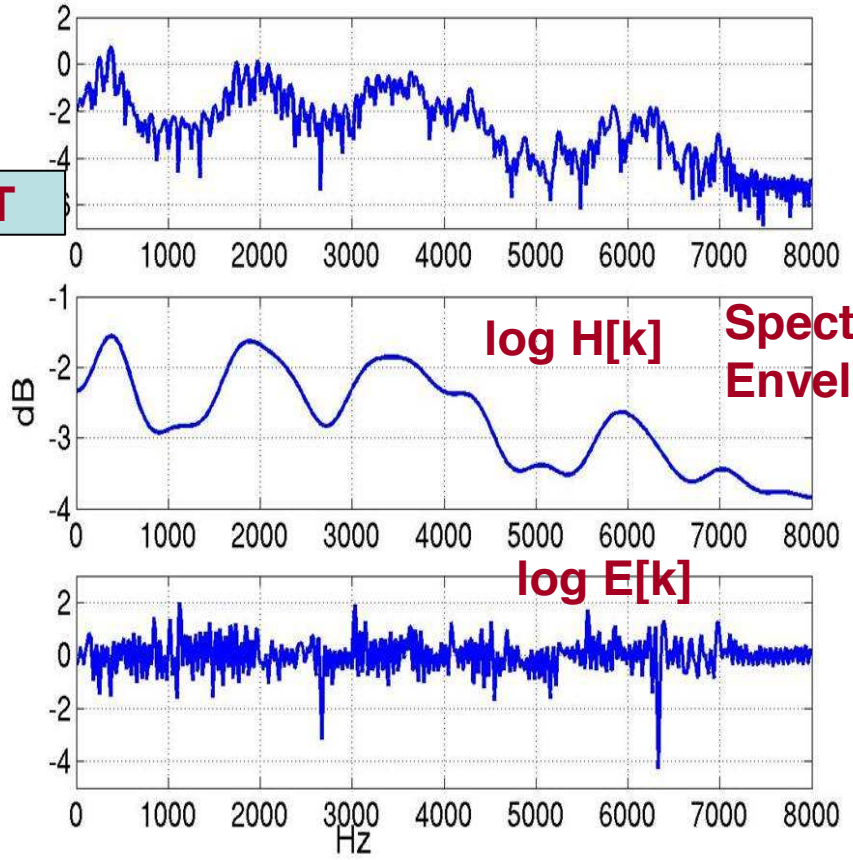


A pseudo-frequency axis

log X[k] = log H[k] + log E[k]

Spectrum

IFFT

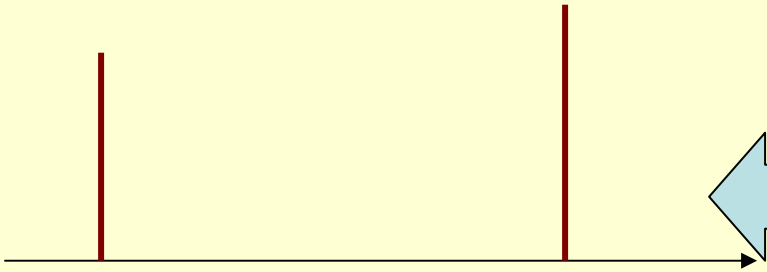


Spectral Envelope

Spectral details

Play a Mathematical Trick

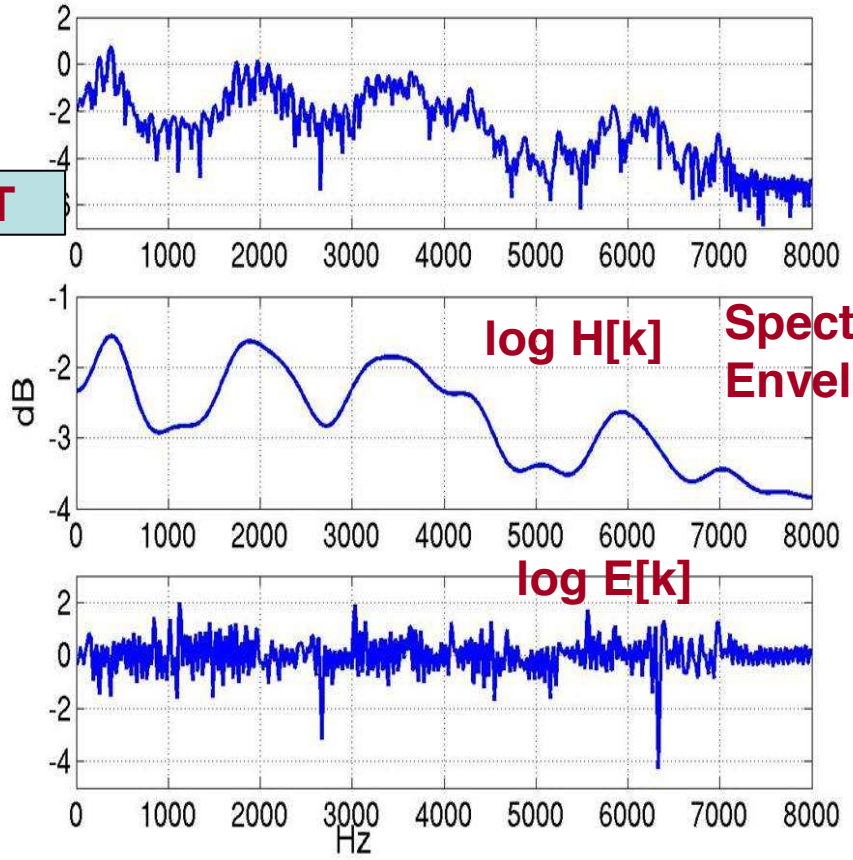
x[k] = h[k] + e[k]



IFFT

log X[k] = log H[k] + log E[k]

Spectrum



Spectral Envelope

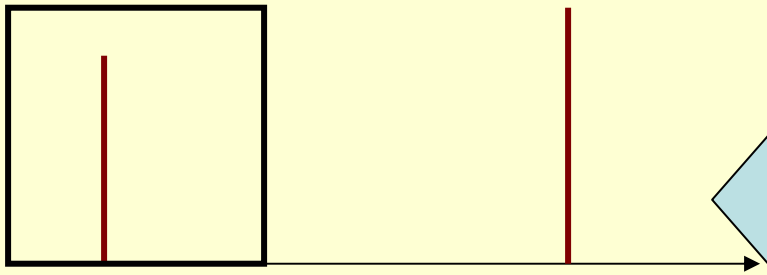
Spectral details

In practice all you have access to only log X[k] and hence you can obtain x[k]

A pseudo-frequency axis

Play a Mathematical Trick

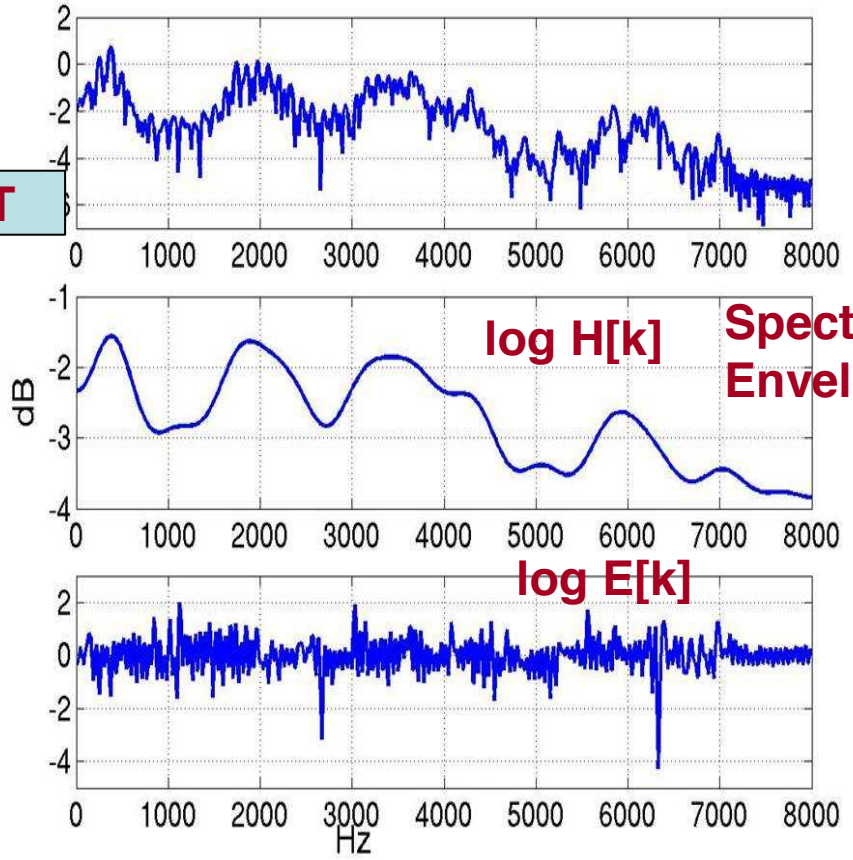
x[k] = h[k] + e[k]



IFFT

log X[k] = log H[k] + log E[k]

Spectrum



Spectral Envelope

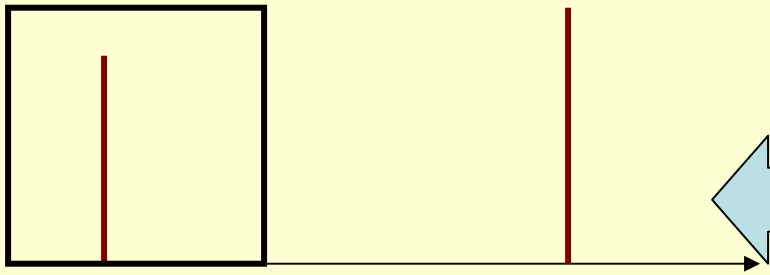
Spectral details

If you know x[k] Filter the low frequency region to get h[k]

A pseudo-frequency axis

Play a Mathematical Trick

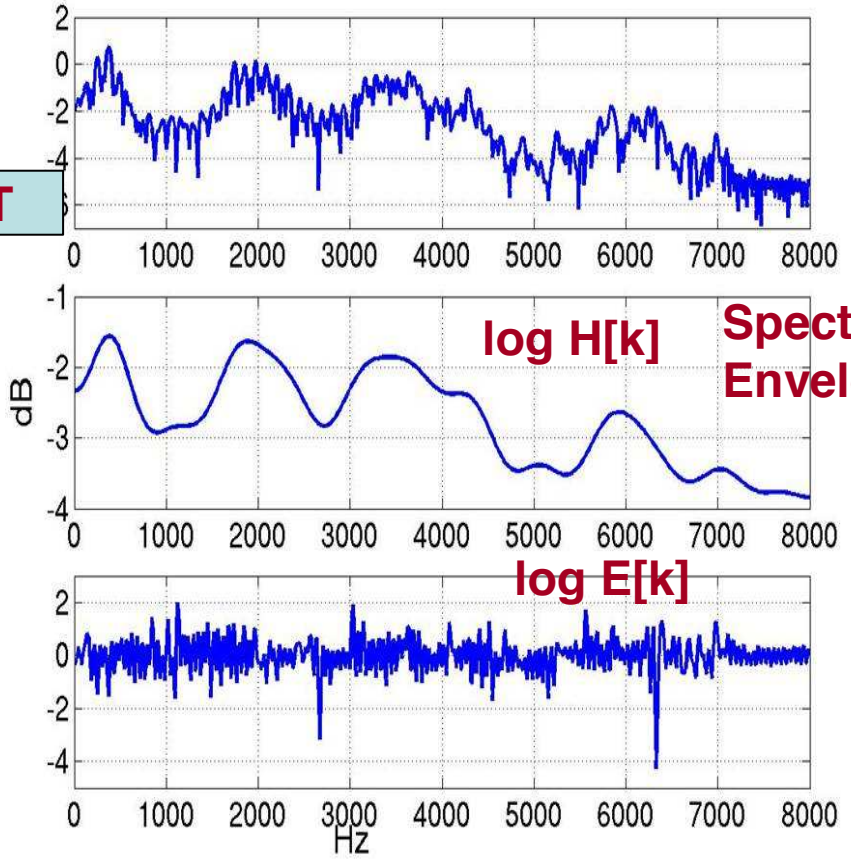
x[k] = h[k] + e[k]



A pseudo-frequency axis

IFFT

log X[k] = log H[k] + log E[k]



- x[k] is referred to as Cepstrum
- h[k] is obtained by considering the low frequency region of x[k].
- h[k] represents the spectral envelope and is widely used as feature for speech recognition

Cepstral Analysis

$$X[k] = H[k]E[k]$$

$$\| X[k] \| = \| H[k] \| \ \| E[k] \|$$

$\| . \|$ – denotes magnitude

Take Log on both sides

$$\log \| X[k] \| = \log \| H[k] \| + \log \| E[k] \|$$

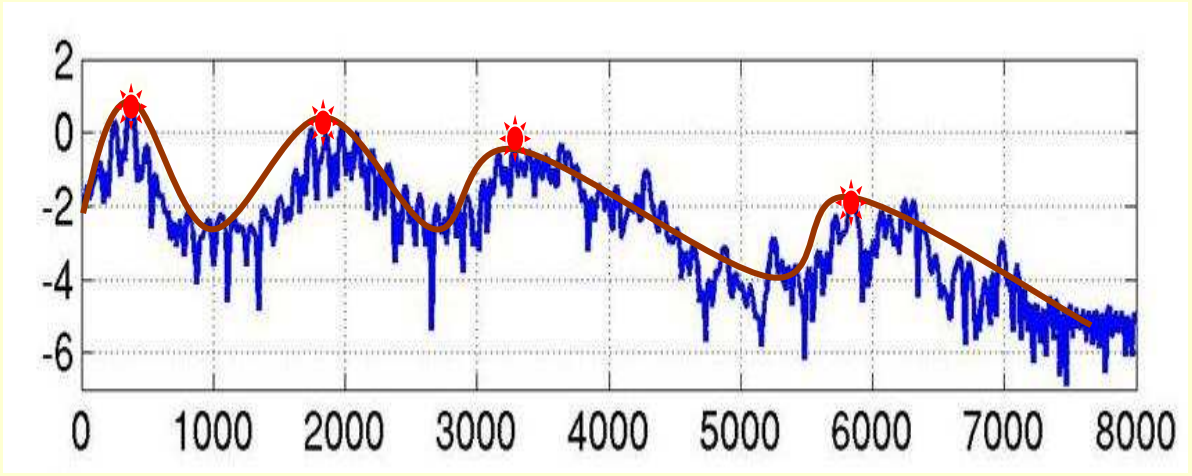
Taking inverse FFT on both sides

$$x[k] = h[k] + e[k]$$

Mel-Frequency Analysis

Review: What we did

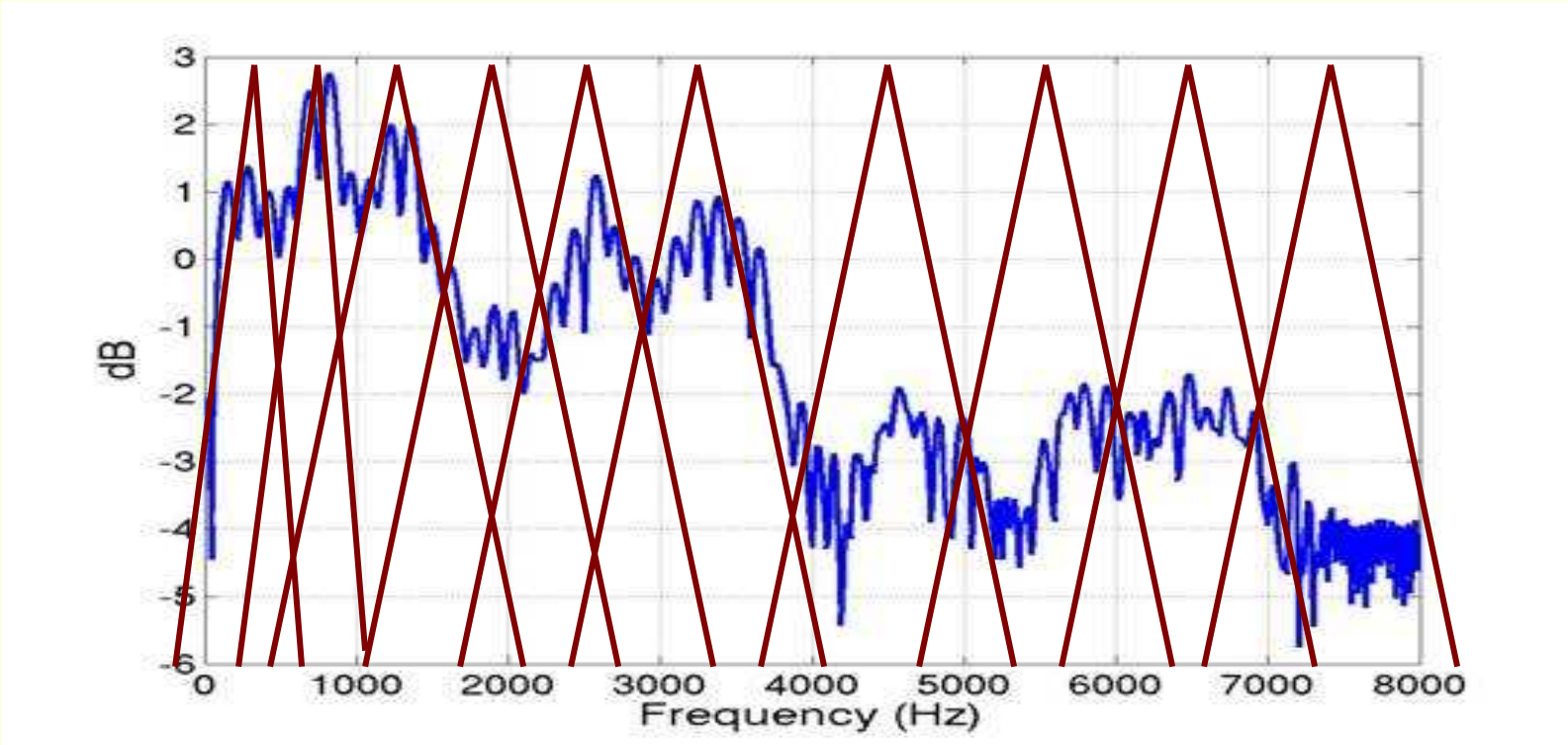
- We captured spectral envelope (curve connecting all formants)
- BUT: Perceptual experiments say human ear concentrates on certain regions rather than using whole of the spectral envelope….



Mel-Frequency Analysis

- Mel-Frequency analysis of speech is based on human perception experiments
- It is observed that human ear acts as filter
  - It concentrates on only certain frequency components
- These filters are non-uniformly spaced on the frequency axis
  - More filters in the low frequency regions
  - Less no. of filters in high frequency regions

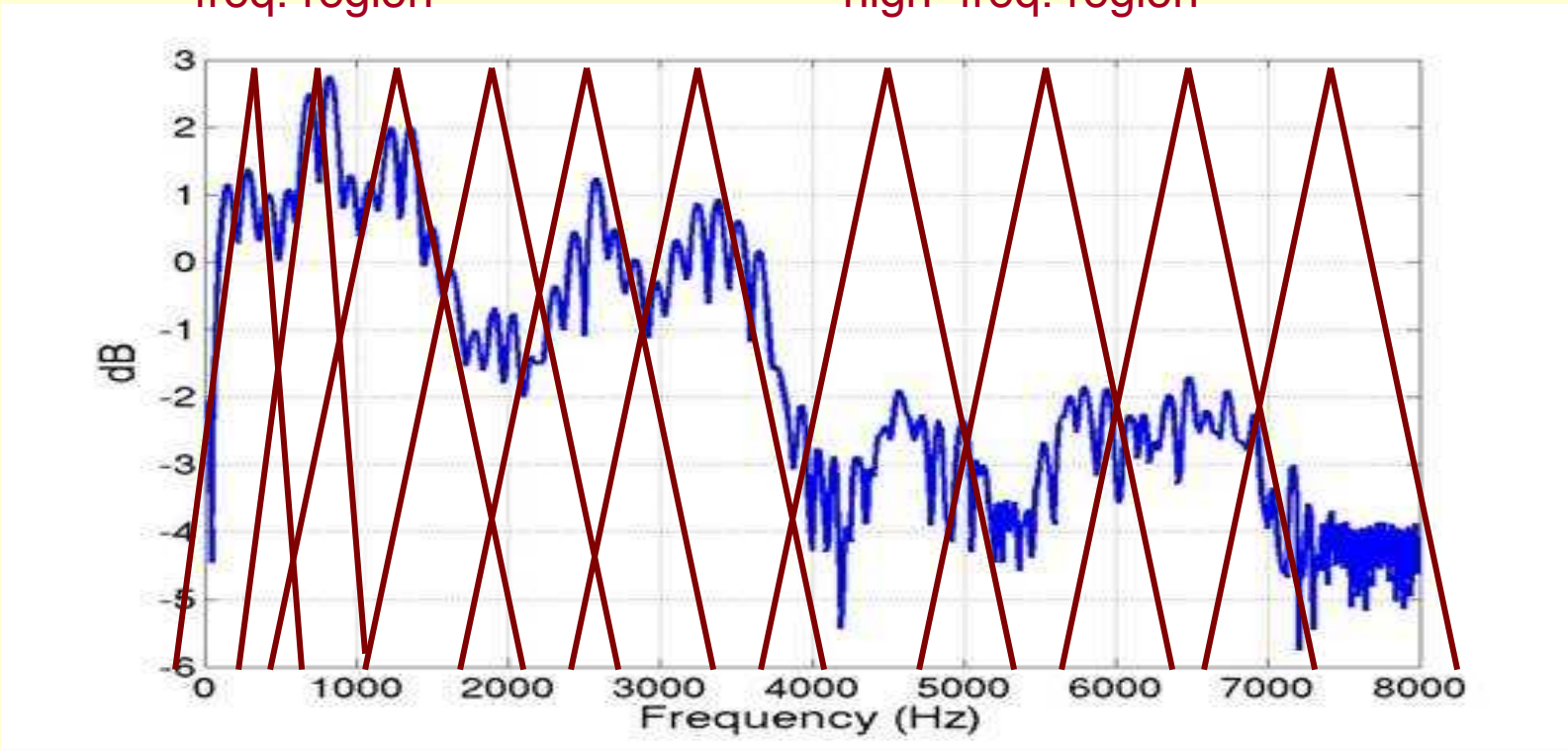
Mel-Frequency Filters



Mel-Frequency Filters

More no. of filters in low freq. region

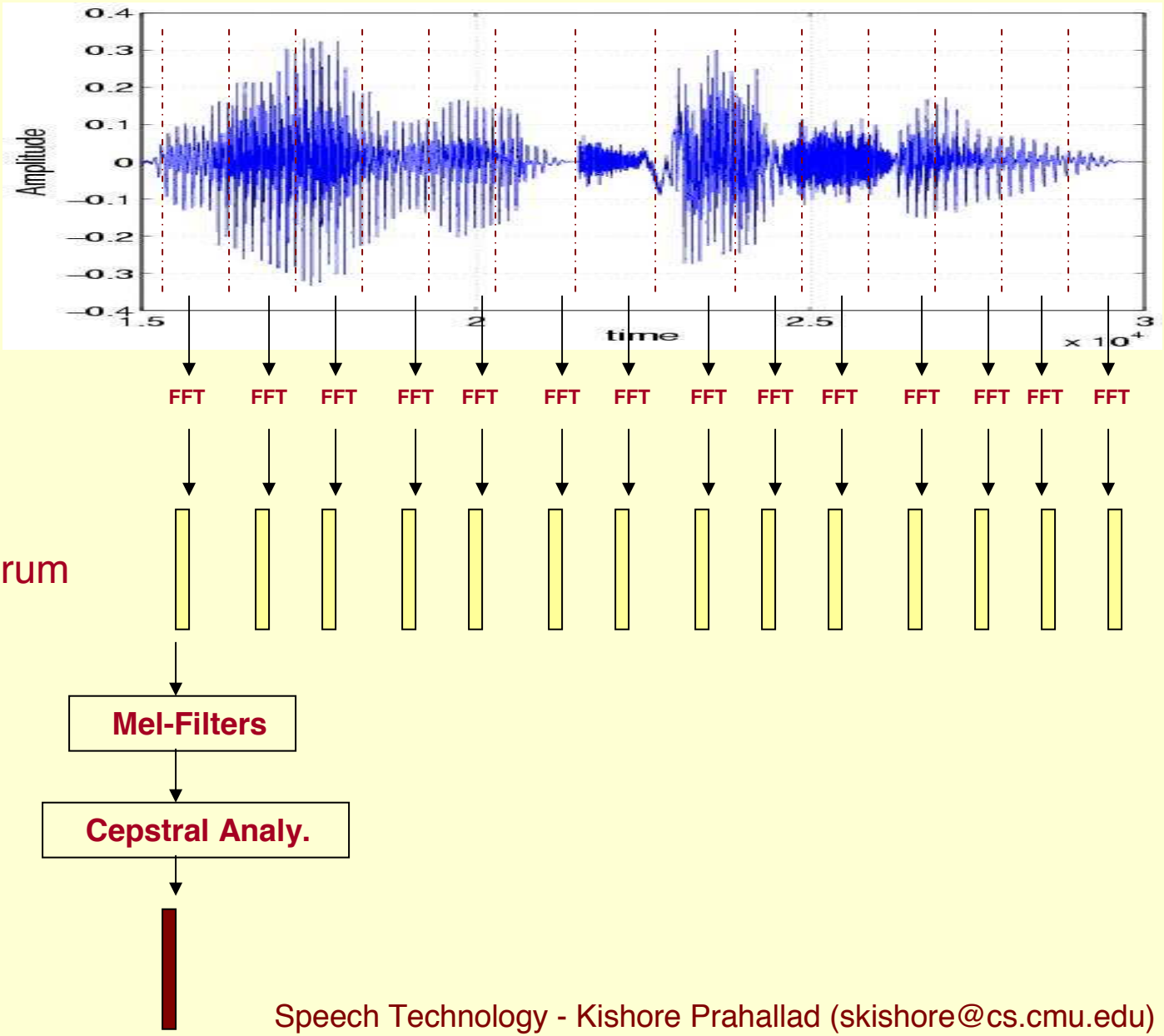
Lesser no. of filters in high freq. region



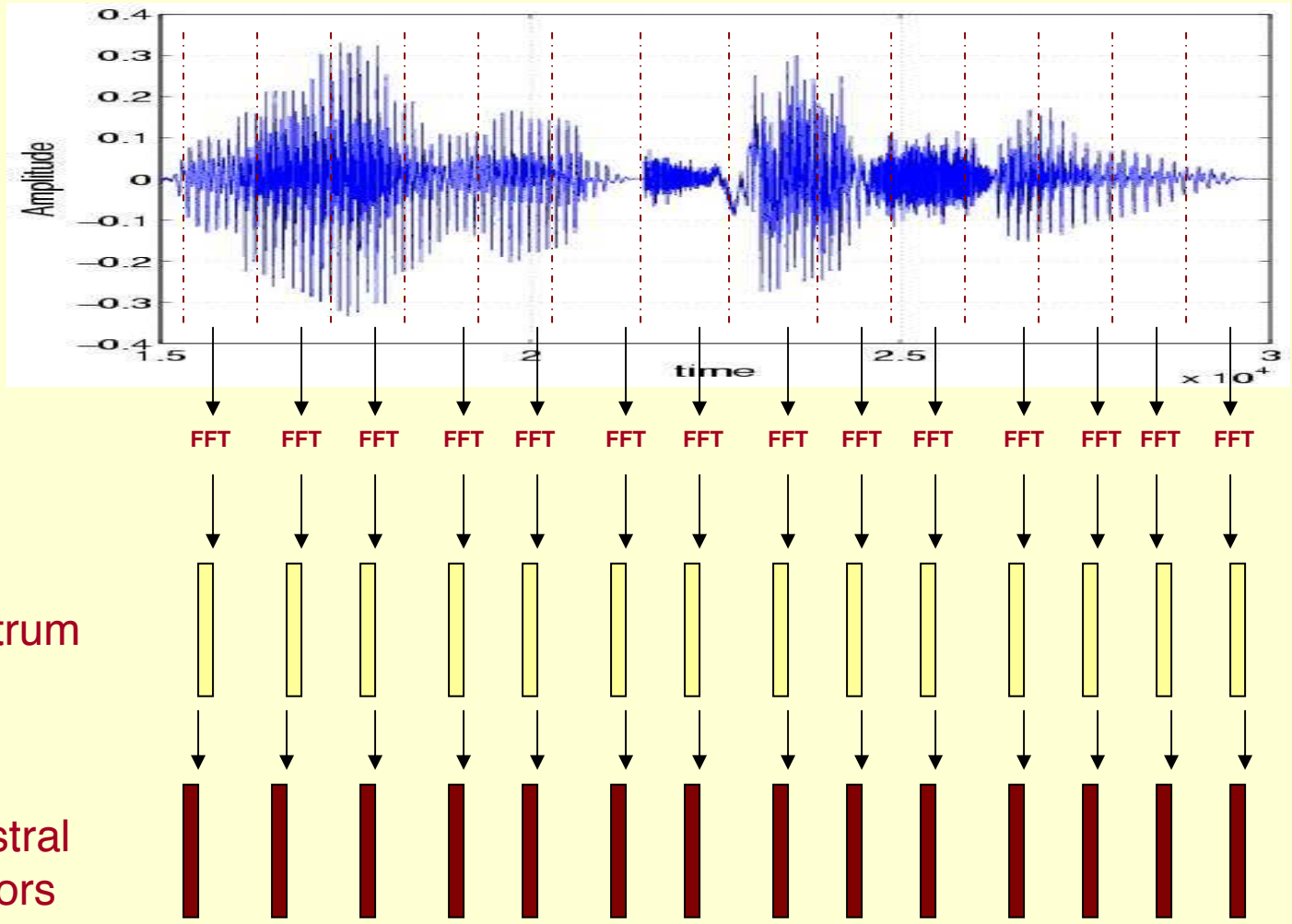
Mel-Frequency Cepstral Coefficients (MFCC)

- Spectrum → Mel-Filters → Mel-Spectrum
- Say log X[k] = log (Mel-Spectrum)
- NOW perform Cepstral analysis on log X[k]
  - log X[k] = log H[k] + log E[k]
  - Taking IFFT
  - x[k] = h[k] + e[k]
- Cepstral coefficients h[k] obtained for Mel-spectrum are referred to as Mel-Frequency Cepstral Coefficients often denoted by *MFCC*

Speech signal represented as a sequence of spectral vectors



Speech signal represented as a sequence of CEPSTRAL vectors



Why we are going to use MFCC

- Speech synthesis
  - Used for joining two speech segments S1 and S2
  - Represent S1 as a sequence of MFCC
  - Represent S2 as a sequence of MFCC
  - Join at the point where MFCCs of S1 and S2 have minimal Euclidean distance
- Used in speech recognition
  - MFCC are mostly used features in state-of-art speech recognition system

Summary: Process of Feature Extraction

- Speech is analyzed over short analysis window
- For each short analysis window a spectrum is obtained using FFT
- Spectrum is passed through Mel-Filters to obtain Mel-Spectrum
- Cepstral analysis is performed on Mel-Spectrum to obtain Mel-Frequency Cepstral Coefficients
- Thus speech is represented as a sequence of Cepstral vectors
- It is these Cepstral vectors which are given to pattern classifiers for speech recognition purpose

Additional Reading

- Chapter 6
  - Pg: 273 – 281
  - Pg: 304 – 311
  - Pg: 314 - 316