

Speech Signal Analysis

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Automatic Speech Recognition— ASR Lectures 2&3
17,21 January 2019

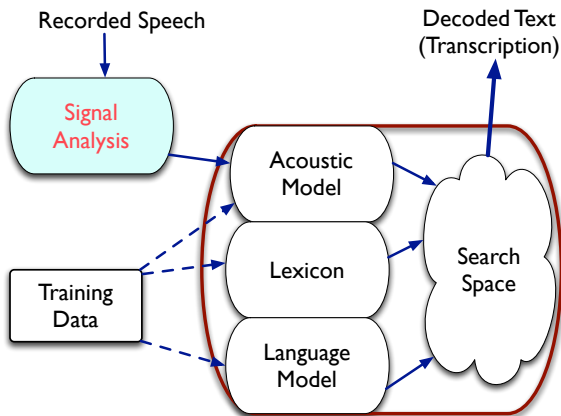
Speech Signal Analysis for ASR

- Features for ASR
- Spectral analysis
- Cepstral analysis
- Standard features for ASR: FBANK, MFCCs and PLP analysis
- Dynamic features

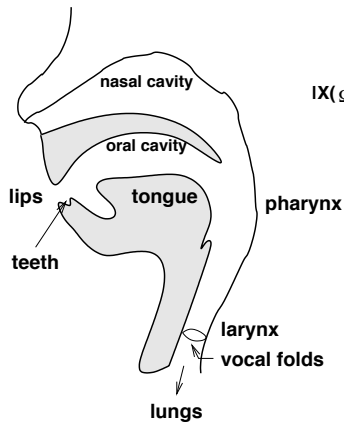
Reading:

- Jurafsky & Martin, sec 9.3
- P Taylor, *Text-to-Speech Synthesis*, chapter 12, signal processing background chapter 10

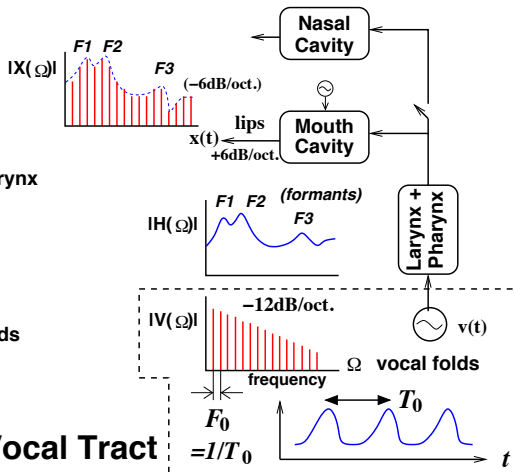
Speech signal analysis for ASR



Speech production model



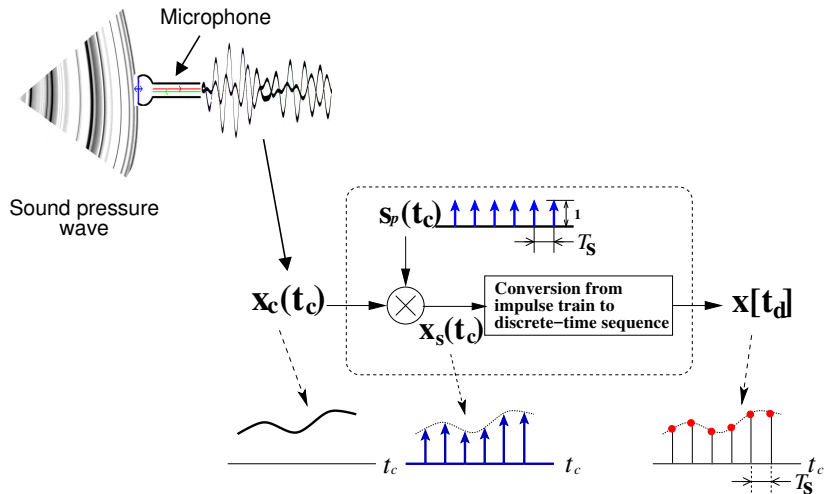
Vocal Organs & Vocal Tract



(F_0 : fundamental frequency)

A/D conversion — Sampling

Convert analogue signals in digital form



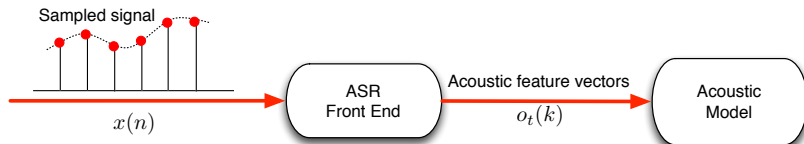
Things to know:

- Sampling Frequency ($F_s = 1/T_s$)

Speech	Sufficient F_s
Microphone voice ($< 10kHz$)	20 kHz
Telephone voice ($< 4kHz$)	8 kHz

- Analogue low-pass filtering to avoid 'aliasing'
NB: the cut-off frequency should be less than the
Nyquist frequency ($= F_s/2$)

Acoustic Features for ASR

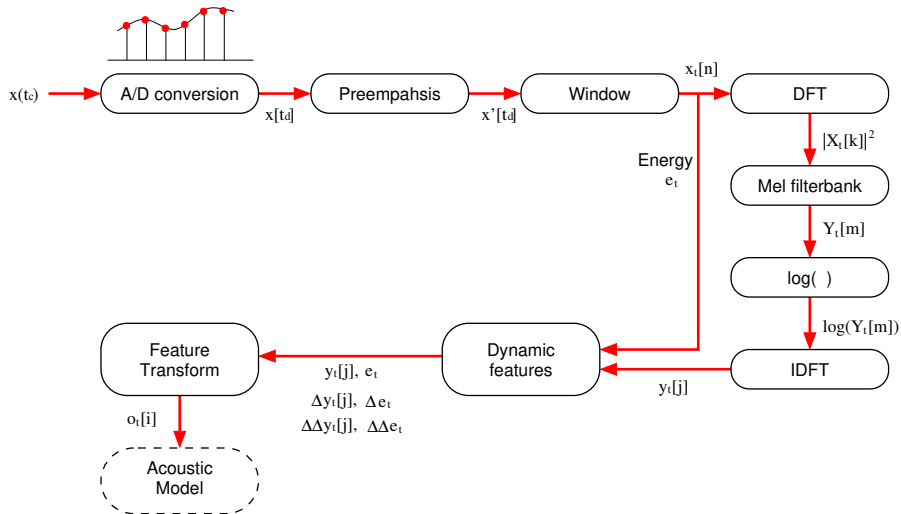


Speech signal analysis to produce a sequence of acoustic feature vectors

Desirable characteristics of acoustic features used for ASR:

- Features should contain sufficient information to distinguish between phones
 - good time resolution (10ms)
 - good frequency resolution (20 ~ 40 channels)
- Be separated from F_0 and its harmonics
- Be robust against speaker variation
- Be robust against noise or channel distortions
- Have good “pattern recognition characteristics”
 - low feature dimension
 - features are independent of each other (NB: this applies to GMMs, but not required for NN-based systems)

MFCC-based front end for ASR

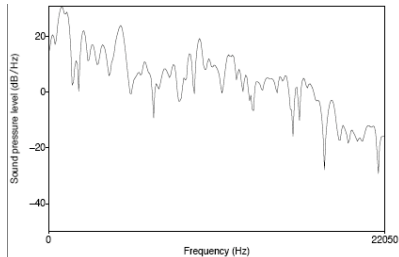
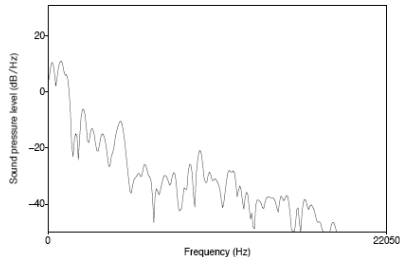


Pre-emphasis and spectral tilt

- Pre-emphasis increases the magnitude of higher frequencies in the speech signal compared with lower frequencies
- *Spectral Tilt*
 - The speech signal has more energy at low frequencies (for voiced speech)
 - This is due to the glottal source (see the figure)
- Pre-emphasis (first-order) filter boosts higher frequencies:

$$x'[t_d] = x[t_d] - \alpha x[t_d - 1] \qquad 0.95 < \alpha < 0.99$$

Pre-emphasis: example



Vowel /aa/ - time slice of the spectrum

(Jurafsky & Martin, fig. 9.9)

Windowing

- The speech signal is constantly changing (non-stationary)
- Signal processing algorithms usually assume that the signal is stationary
- Piecewise stationarity: model speech signal as a sequence of **frames** (each assumed to be stationary)
- **Windowing**: multiply the full waveform $s[n]$ by a window $w[n]$ (in time domain):

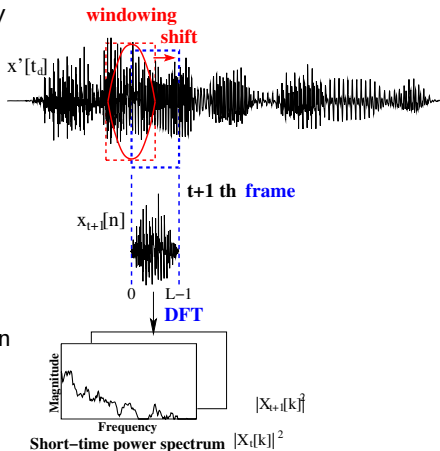
$$x[n] = w[n] s[n] \quad (x_t[n] = w[n] x'[t_d + n])$$

- Simply cutting out a short segment (frame) from $s[n]$ is a rectangular window — causes discontinuities at the edges of the segment
- Instead, a tapered window is usually used
e.g. *Hamming* ($\alpha = 0.46164$) or *Hanning* ($\alpha = 0.5$) window

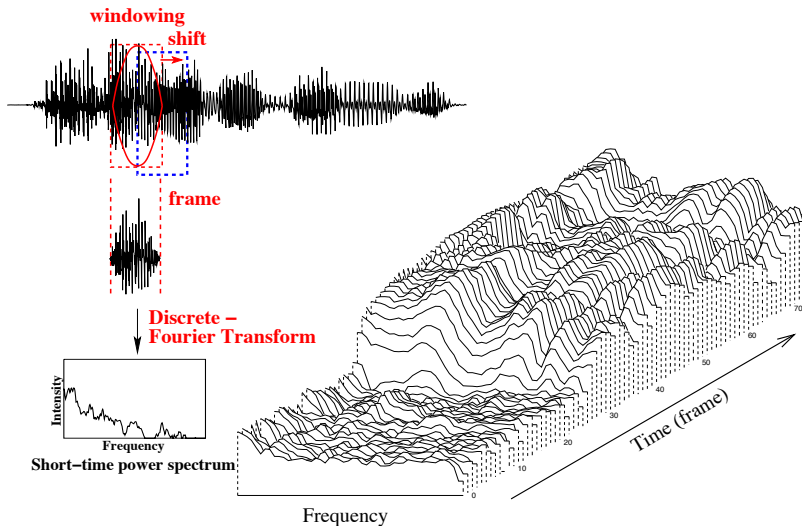
$$w[n] = (1 - \alpha) - \alpha \cos\left(\frac{2\pi n}{L-1}\right) \quad L : \text{window width}$$

Windowing and spectral analysis

- Window the signal $x'[t_d]$ into frames $x_t[n]$ and apply Fourier Transform to each segment.
 - Short frame width:
wide-band,
high time resolution,
low frequency resolution
 - Long frame width:
narrow-band,
low time resolution,
high frequency resolution
- For ASR:
 - frame width $\sim 25ms$
 - frame shift $\sim 10ms$



Short-time spectral analysis



Discrete Fourier Transform (DFT)

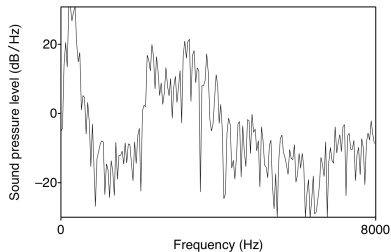
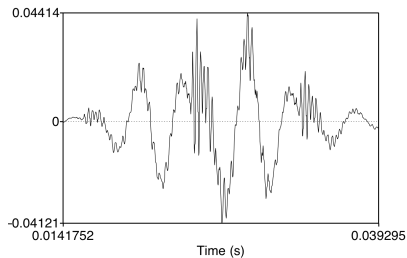
- Purpose: extracts spectral information from a windowed signal (i.e. how much energy at each frequency band)
- Input: windowed signal $x[0], \dots, x[L-1]$ (time domain)
- Output: a complex number $X[k]$ for each of N frequency bands representing magnitude and phase for the k th frequency component (frequency domain)
- Discrete Fourier Transform (DFT):

$$X[k] = \sum_{n=0}^{N-1} x[n] \exp\left(-j \frac{2\pi}{N} kn\right)$$

NB: $\exp(j\theta) = e^{j\theta} = \cos(\theta) + j \sin(\theta)$

- Fast Fourier Transform (FFT) — efficient algorithm for computing DFT when N is a power of 2, and $N \geq L$.

DFT Spectrum



25ms Hamming window of vowel /iy/ and its spectrum computed by DFT

(Jurafsky and Martin, fig 9.12)

Wide-band and narrow-band spectrograms

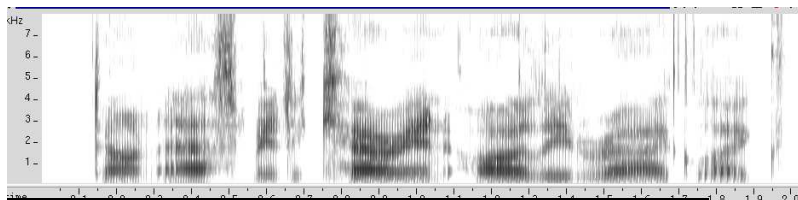


Figure 12.8 Wide band spectrogram window width = 2.5ms

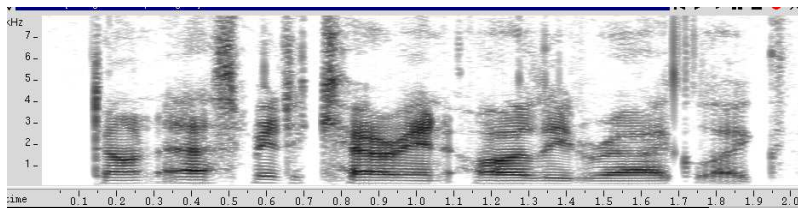
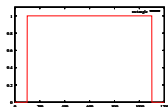


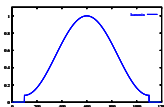
Figure 12.9 Narrow band spectrogram window width = 25ms

(Taylor, figs 12.8, 12.9)

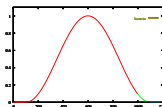
Effect of windowing — time domain



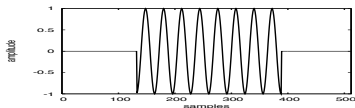
Rectangular



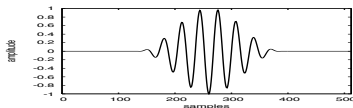
Hamming



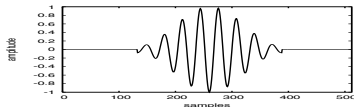
Hanning



(a) Rectangular window



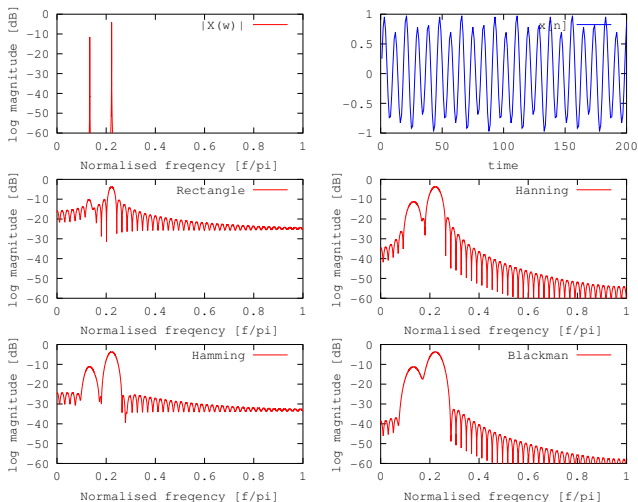
(b) Hanning window



(c) Hamming window

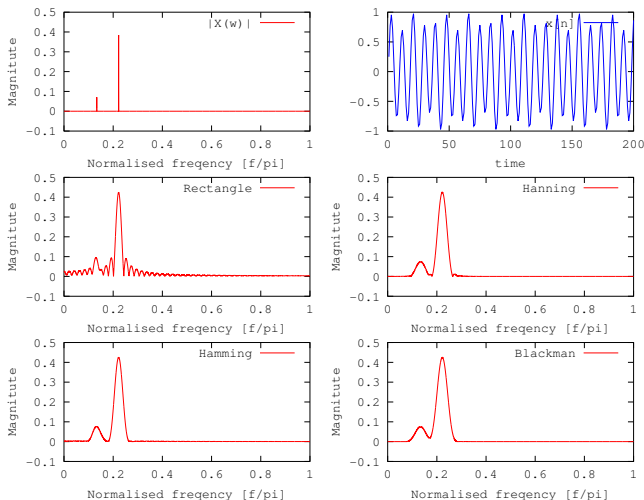
(Taylor, fig 12.1)

Effect of windowing — frequency domain



$$x(t) = 0.15 \sin(2\pi f_1 t) + 0.85 \sin(2\pi f_2 t + 0.3)$$
$$f_1 = 0.13, f_2 = 0.22$$

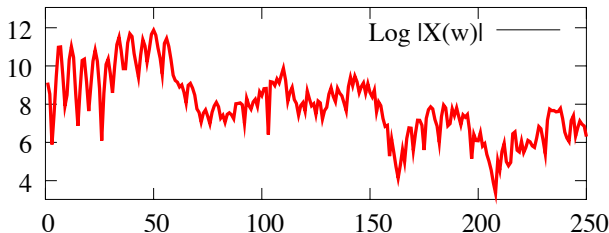
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$$x(t) = 0.15 \sin(2\pi f_1 t) + 0.85 \sin(2\pi f_2 t + 0.3)$$
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DFT Spectrum Features for ASR

- Equally-spaced frequency bands — but human hearing less sensitive at higher frequencies (above $\sim 1000\text{Hz}$)
- The estimated power spectrum contains harmonics of F_0 , which makes it difficult to estimate the envelope of the spectrum



- Frequency bins of STFT are highly correlated each other, i.e. power spectrum representation is highly redundant

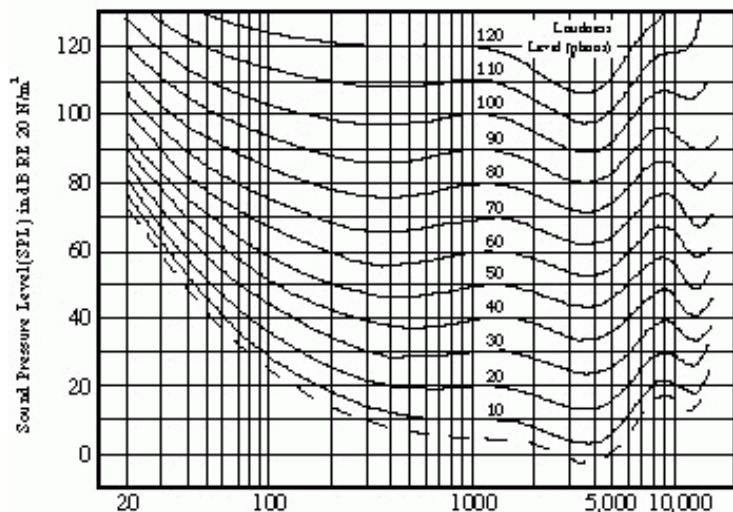
Physical quality	Perceptual quality
Intensity	Loudness
Fundamental frequency	Pitch
Spectral shape	Timbre
Onset/offset time	Timing
Phase difference in binaural hearing	Location

Technical terms

- equal-loudness contours
- masking
- auditory filters (critical-band filters)
- critical bandwidth

Equal loudness contour

Fletcher-Munson Free Field Equal Loudness Contours

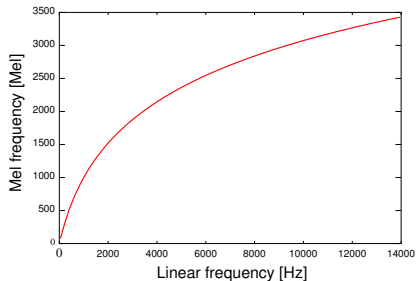


Nonlinear frequency scaling

Human hearing is less sensitive to higher frequencies — thus human perception of frequency is nonlinear

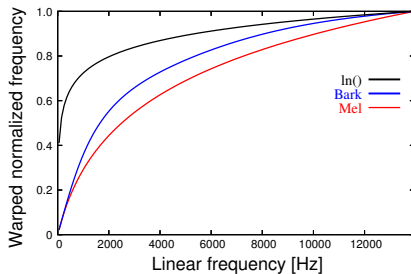
Mel scale

$$M(f) = 1127 \ln(1 + f/700)$$



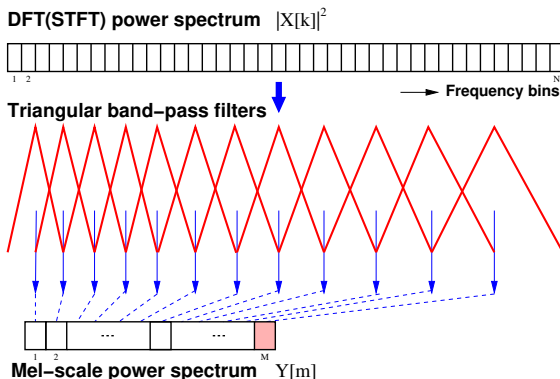
Bark scale

$$b(f) = 13 \arctan(0.00076f) + 3.5 \arctan((f/7500)^2)$$



Mel-Filter Bank

- Apply a mel-scale filter bank to DFT power spectrum to obtain mel-scale power spectrum
- Each filter collects energy from a number of frequency bands in the DFT
- Linearly spaced < 1000 Hz, logarithmically spaced > 1000 Hz



$$Y_t[m] = \sum_{k=1}^N W_m[k] |X_t[k]|^2$$

where k : DFT bin number $(1, \dots, N)$
 m : mel-filter bank number $(1, \dots, M)$.

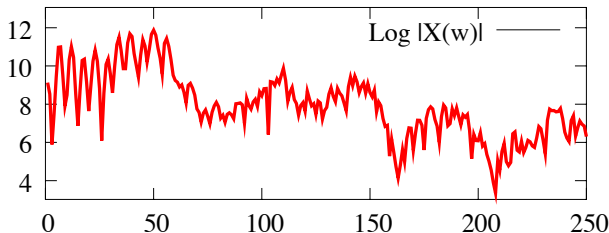
- How many number of mel-filter channels?
 - ≈ 20 for GMM-HMM based ASR
 - $20 \sim 40$ for DNN (+HMM) based ASR

Log Mel Power Spectrum

- Compute the log magnitude squared of each mel-filter bank output: $\log Y[m]$
 - Taking the log compresses the dynamic range
 - Human sensitivity to signal energy is logarithmic — i.e. humans are less sensitive to small changes in energy at high energy than small changes at low energy
 - Log makes features less variable to acoustic coupling variations
 - Removes phase information — not important for speech recognition (not everyone agrees with this)
- Aka “log mel-filter bank outputs” or “FBANK features”, which are widely used in recent DNN-HMM based ASR systems

DFT Spectrum Features for ASR

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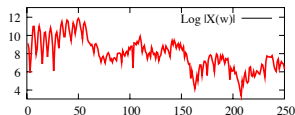


- Frequency bins of STFT are highly correlated each other, i.e. power spectrum representation is highly redundant

- Source-Filter model of speech production
 - **Source:** Vocal cord vibrations create a glottal source waveform
 - **Filter:** Source waveform is passed through the vocal tract: position of tongue, jaw, etc. give it a particular shape and hence a particular filtering characteristic
- Source characteristics (F_0 , dynamics of glottal pulse) do not help to discriminate between phones
- The filter specifies the position of the articulators
- ... and hence is directly related to phone discrimination
- Cepstral analysis enables us to separate source and filter

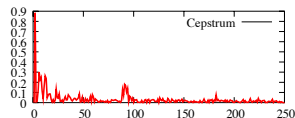
Cepstral Analysis

Split power spectrum into spectral envelope and F_0 harmonics.



Log spectrum (freq domain)

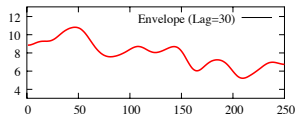
⇓ Inverse Fourier Transform



Cepstrum (time domain) (quefreny)

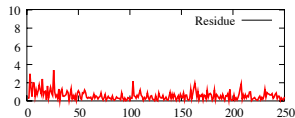
⇓ Liftering to get low/high part
(lifter: filter used in cepstral domain)

⇓ Fourier Transform



Smoothed log spectrum (freq domain)
[low-part of cepstrum]

+



Fine structure
[high-part of cepstrum]

The Cepstrum

- Cepstrum obtained by applying inverse DFT to log magnitude spectrum (may be mel-scaled)
- Cepstrum is time-domain (we talk about quefrency)
- Inverse DFT:

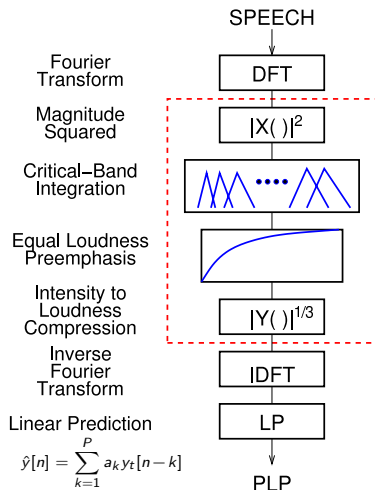
$$x[n] = \frac{1}{N} \sum_{k=0}^{N-1} X[k] \exp \left(j \frac{2\pi}{N} nk \right)$$

- Since log power spectrum is real and symmetric the inverse DFT is equivalent to a discrete cosine transform (DCT)

$$y_t[n] = \sum_{m=0}^{M-1} \log(Y_t[m]) \cos \left(n(m+0.5) \frac{\pi}{M} \right), \quad n = 0, \dots, J$$

- Smoothed spectrum: transform to cepstral domain, truncate, transform back to spectral domain
- Mel-frequency cepstral coefficients (MFCCs): use the cepstral coefficients directly
 - Widely used as acoustic features in HMM-based ASR
 - First 12 MFCCs are often used as the feature vector (removes F0 information)
 - Less correlated than spectral features — easier to model than spectral features
 - Very compact representation — 12 features describe a 20ms frame of data
 - For standard HMM-based systems, MFCCs result in better ASR performance than filter bank or spectrogram features
 - MFCCs are not robust against noise

PLP — Perceptual Linear Prediction



- PLP (Hermansky, JASA 1990)
- Uses equal loudness pre-emphasis and cube-root compression (motivated by perceptual results) rather than log compression
- Uses linear predictive auto-regressive modelling to obtain cepstral coefficients
- PLP has been shown to lead to
 - slightly better ASR accuracy
 - slightly better noise robustness

compared with MFCCs

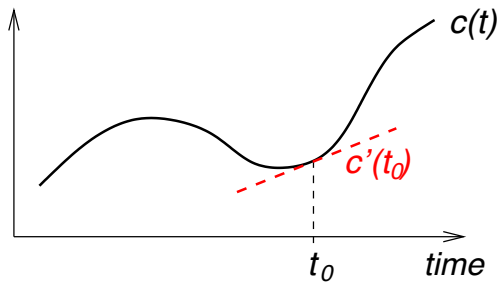
Dynamic features

- Speech is not constant frame-to-frame, so we can add features to do with how the cepstral coefficients change over time
- $\Delta*$, Δ^2* are delta features (dynamic features / time derivatives)
- Simple calculation of delta features $d(t)$ at time t for cepstral feature $c(t)$ (e.g. $y_t[j]$):

$$d(t) = \frac{c(t+1) - c(t-1)}{2}$$

- More sophisticated approach estimates the temporal derivative by using regression to estimate the slope (typically using 4 frames each side)
- “Standard” ASR features (for GMM-based systems) are 39 dimensions:
 - 12 MFCCs, and energy
 - 12 Δ MFCCs, Δ energy
 - 12 Δ^2 MFCCs, Δ^2 energy

Estimating dynamic features



Feature Transforms

- Orthogonal transformation (orthogonal bases)
 - **DCT** (discrete cosine transform)
 - **PCA** (principal component analysis)
- Transformation based on the bases that maximises the separability between classes.
 - **LDA** (linear discriminant analysis) / Fisher's linear discriminant
 - **HLDA** (heteroscedastic linear discriminant analysis)

Feature Normalisation

- **Basic Idea:** Transform the features to reduce mismatch between training and test
- *Cepstral Mean Normalisation* (CMN): subtract the average feature value from each feature, so each feature has a mean value of 0. makes features robust to some linear filtering of the signal (channel variation)
- *Cepstral Variance Normalisation* (CVN): Divide feature vector by standard deviation of feature vectors, so each feature vector element has a variance of 1
- Cepstral mean and variance normalisation, CMN/CVN:

$$\hat{y}_t[j] = \frac{y_t[j] - \mu(y[j])}{\sigma(y[j])}$$

- Compute mean and variance statistics over longest available segments with the same speaker/channel
- Real time normalisation: compute a moving average

See Tables 1, 2, and 3 in

Jinyu Li, Dong Yu, Jui-Ting Huang, and Yifan Gong,
“Improving Wideband Speech Recognition Using Mixed-Bandwidth
Training Data In CD-DNN-HMM”,
2012 IEEE Workshop in Spoken Language Technology (SLT2012).
<https://doi.org/10.1109/SLT.2012.6424210>

Summary: Speech Signal Analysis for ASR

- Good characteristics of ASR features
- FBANK features
 - Short-time DFT analysis
 - Mel-filter bank
 - Log magnitude squared
 - Widely used for DNN ASR ($M \approx 40$)
- MFCCs - mel frequency cepstral coefficients
 - FBANK features
 - Inverse DFT (DCT)
 - Use first few (12) coefficients
 - Widely used for GMM-HMM ASR
- Delta features (dynamic features)
- 39-dimension feature vector (for GMM-HMM ASR):
MFCC-12 + energy; + Deltas; + Delta-Deltas

- J&M: Daniel Jurafsky and James H. Martin (2008). Speech and Language Processing, Pearson Education (2nd edition).
- Taylor: Paul Taylor (2009). Text-to-Speech Synthesis, Cambridge University Press.
- Hynek Hermansky, "Perceptual linear predictive (PLP) analysis of speech," The Journal of the Acoustical Society of America, Vol.87, No.4, pp.1737–1752, 1980.