Cognitive Media Processing #6

Nobuaki Minematsu

Today's menu

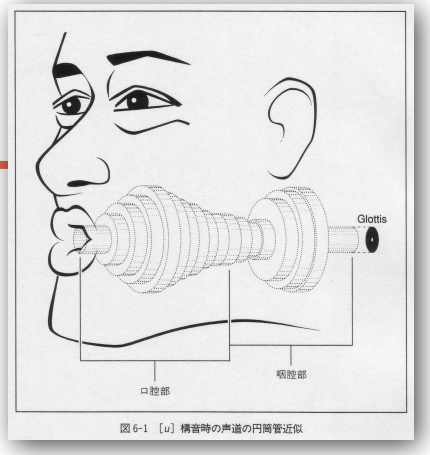
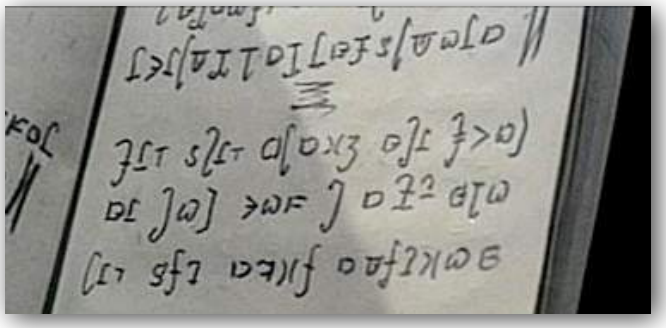
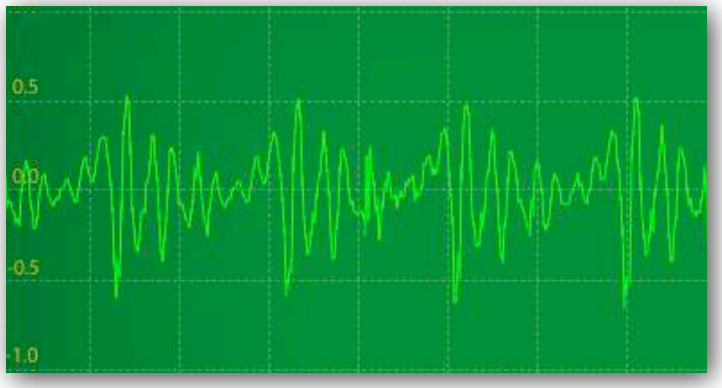


図 6-1 [u] 構音時の声道の円筒管近似

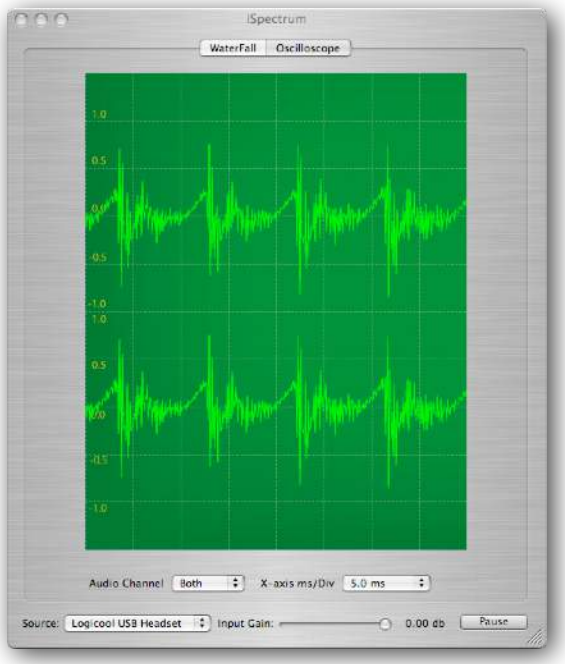
- Speech --> sounds --> vibrations (waves) of air particles
- Fundamentals of phonetics
  - How are vowel sounds produced?
  - Phonetics = articulatory phonetics + acoustic phon. + auditory phon.
- More on articulatory phonetics
  - Observation of speech organs



- More on general phonetics
  - General phonetics = language independent phonetics
  - How to symbolize language sounds found in any language?
- More on acoustic phonetics
  - Vowels as standing waves
    - Resonance frequency = formant frequency
  - Link between acoustic phon. and articulatory phon.
- Summary



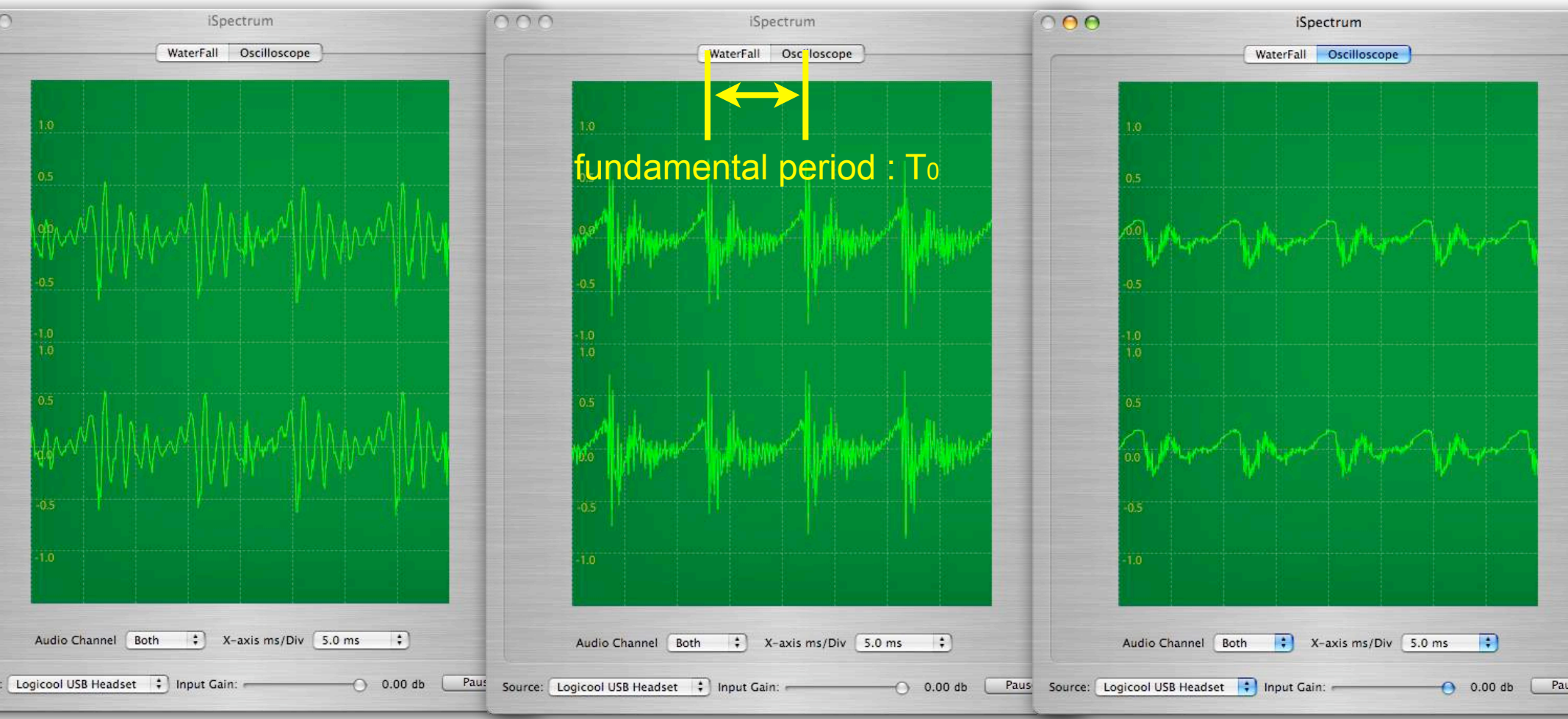
Speech = vibrations of air particles



- The four aspects of tones (sounds)
  - Height of tones (pitch of tones)
    - High tones and low tones
  - Loudness of tones
    - Loud tones and soft tones
  - Duration of tones
    - Long tones and short tones
  - Timbre of tones (color of tones, 音色, 声色)
    - ????
    - If two tones have the same height, the same loudness, and the same duration but the two tones are perceived as different tones, then, the two tones differ in their timbre.
    - /a/ and /i/ /a/ and /a/
      - difference in phoneme, difference in gender

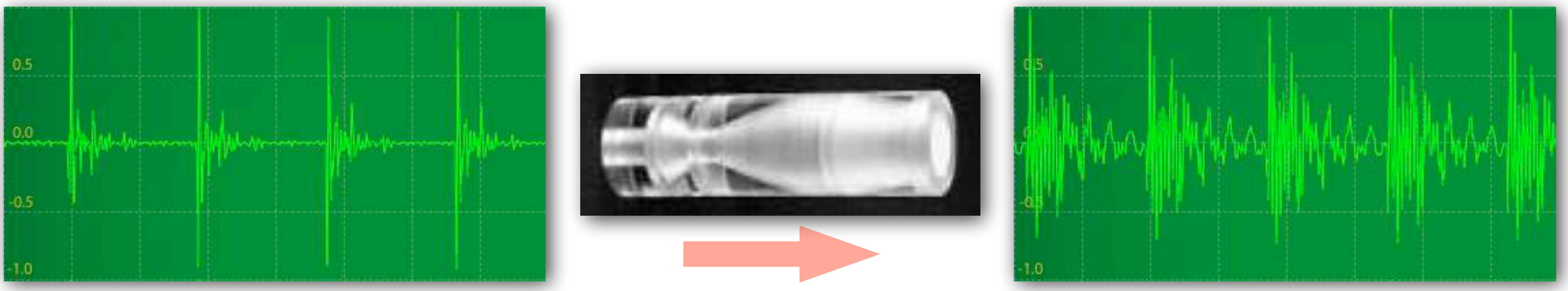
Speech = vibrations of air particles

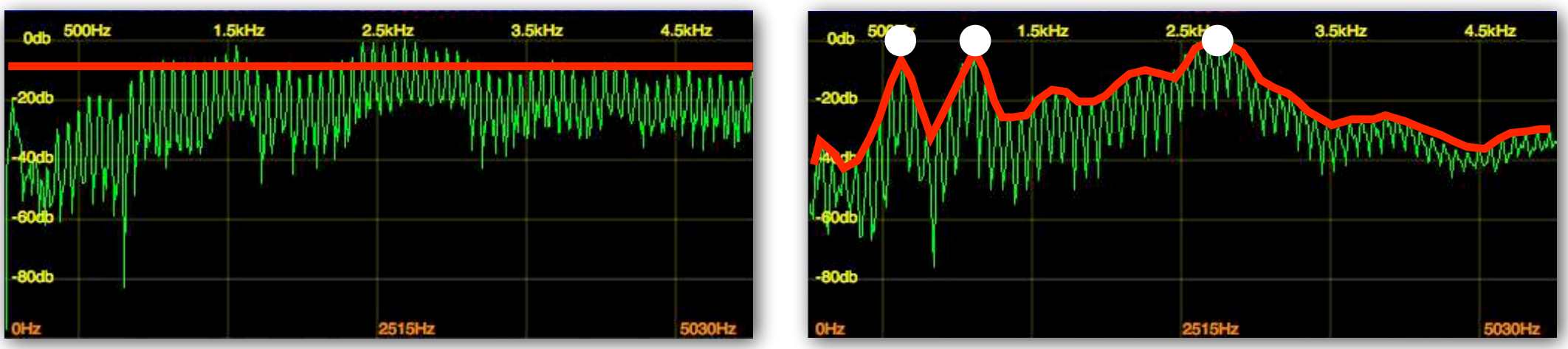
- Close observation of air particle vibration patterns.
  - /a/, /i/, and /u/ with the same height of tone.
  - They are periodic signals (waveforms).



Acoustic phonetics

- Spectrum of a vowel sound





Resonance = concentration of the energy on specific bands that are determined only by the shape of a tube used for sound generation.

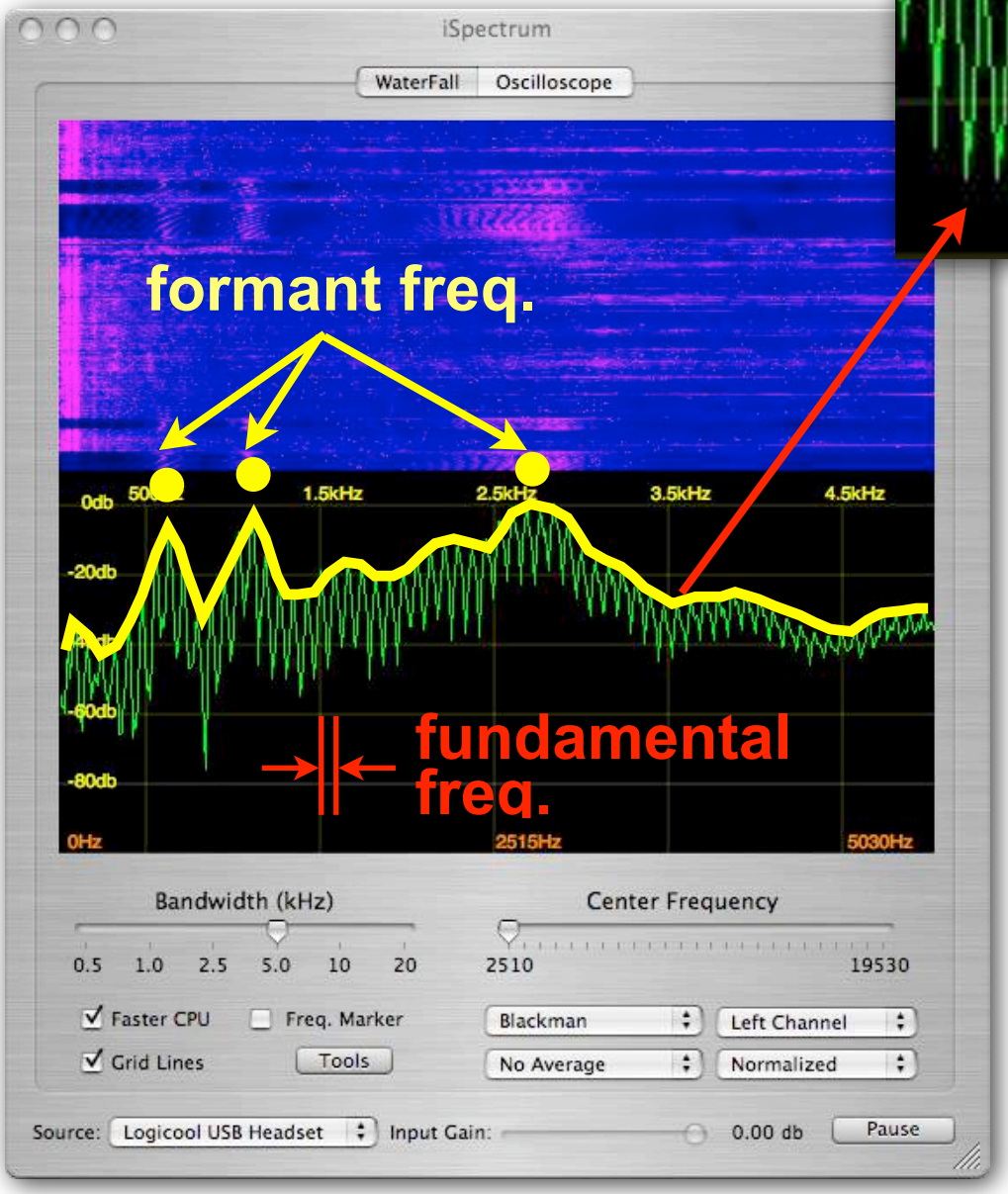
Timbre = energy distribution pattern over the frequency axis

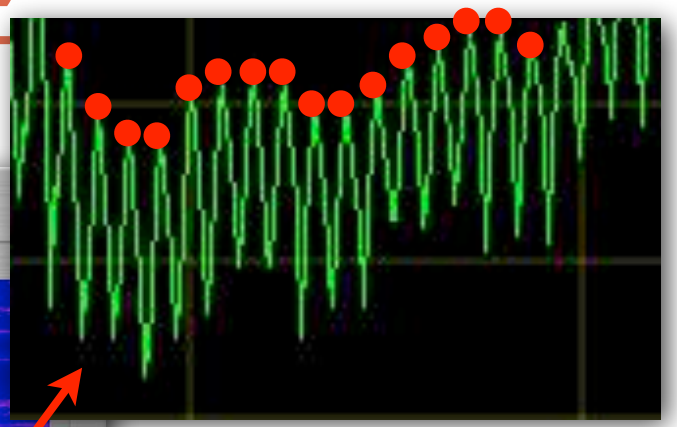
Fundamental frequency (F0) and timbre

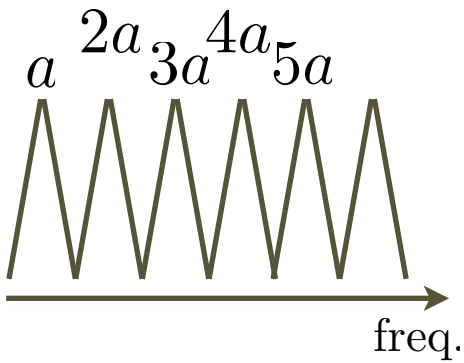
- F0 and timbre observed in the spectrum

喉の形を変えると共振周波数が変わる。つまり，エネルギー分布の様子（パワースペクトル）が変わる。

これを，音響用語では音色と呼ぶ。楽器の違いは音色の違い，母音の違いも音色の違いである。話者の違いもまた，音色の違いである



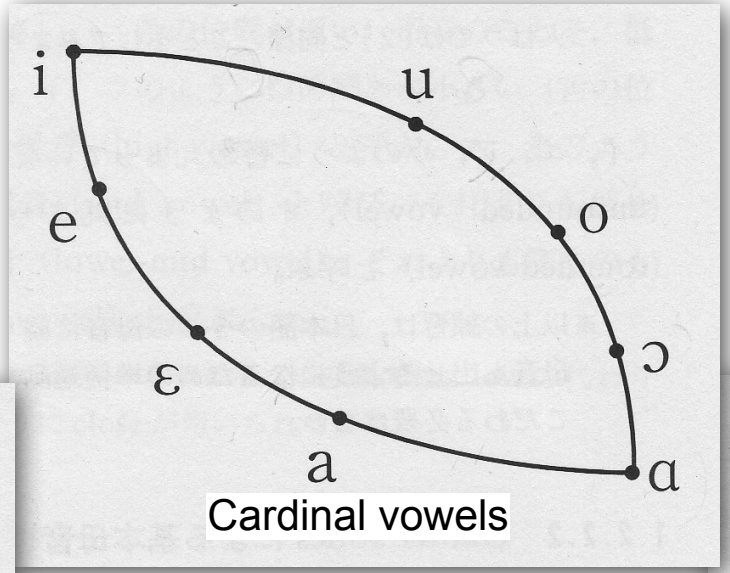




厳密には「音高＝a」であって，ピークの間隔ではない。調波構造が無くても音高は感覚できる。

General phonetics

- 18 fundamental and theoretical vowels -- cardinal vowels
  - Reference vowels used to describe the vowel sounds in a specific language.
    - Theoretically and artificially defined vowels
  - Position of the tongue x lip (un)rounding gives a set of 18 vowels.



Cardinal vowels

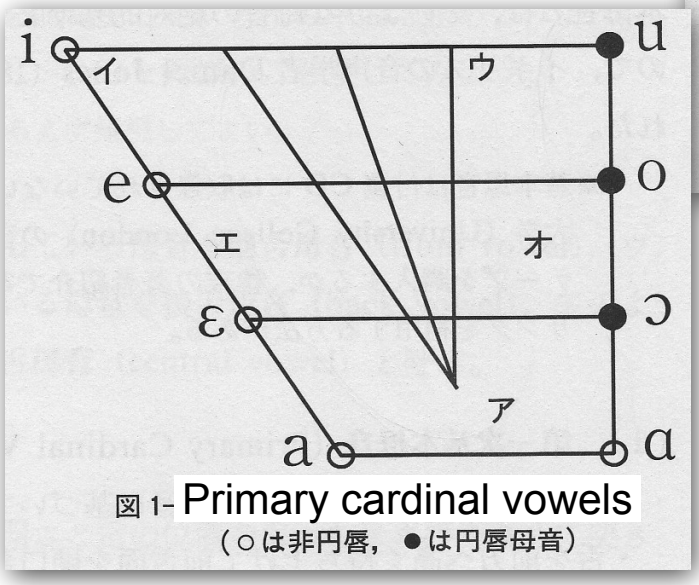
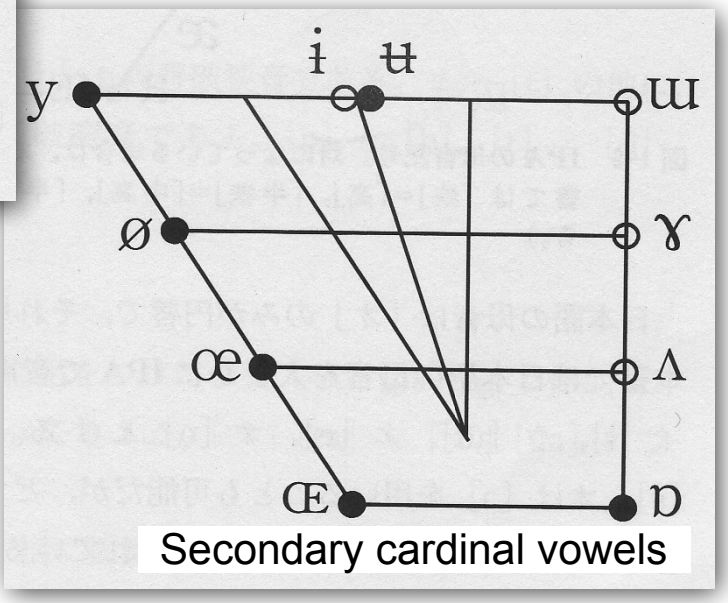


図 1- Primary cardinal vowels
（○は非円唇，●は円唇母音）

●: rounding

○: unrounding



Secondary cardinal vowels

General phonetics

- Classification of consonants
  - Complete or partial closure in the vocal tract.
  - Where and how closure happens in the vocal tract.
    - Where = place of articulation
    - How = manner of articulation
    - Condition of the vocal folds = voiced or unvoiced

place of articulation

manner of articulation

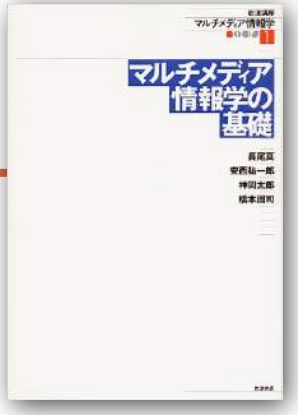
CONSONANTS (PULMONIC)

	Bilabial	Labiodental	Dental	Alveolar	Post-alveolar	Retroflex	Palatal	Velar	Uvular	Pharyngeal	Glottal
Plosive	p b			t d		ʈ ɖ	c ɟ	k g	q ɢ		ʔ
Nasal	m	ɱ		n		ɳ	ɲ	ŋ	ɴ		
Trill	ʙ			r					ʀ		
Tap or Flap				ɾ		ɽ					
Fricative	ɸ β	f v	θ ð	s z	ʃ ʒ	ʂ ʐ	ç ʝ	x ɣ	χ ʁ	ħ ʕ	h ɦ
Lateral fricative				ɬ ɮ							
Approximant		ʋ		ɹ		ɻ	j	ɰ			
Lateral approximant				l		ɭ	ʎ	ʟ			

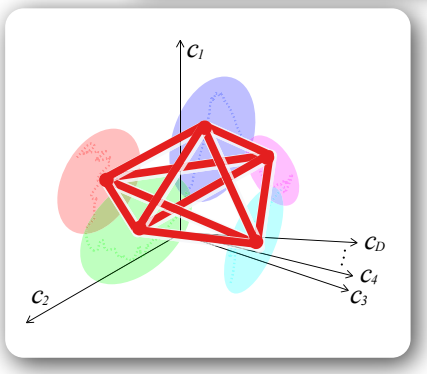
Where symbols appear in pairs, the one to the right represents a voiced consonant. Shaded areas denote articulations judged impossible.

http://phonetics.ucla.edu/course/chapter1/flash.html

Title of each lecture

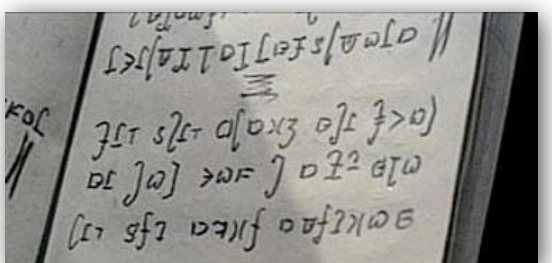


- Theme-1
  - ~~Multimedia information and humans~~
  - ~~Multimedia information and interaction between humans and machines~~
  - ~~Multimedia information used in expressive and emotional processing~~
  - ~~A wonder of sensation - synesthesia -~~
- Theme-2
  - ~~Speech communication technology - articulatory & acoustic phonetics -~~
  - Speech communication technology - speech analysis -
  - Speech communication technology - speech recognition -
  - Speech communication technology - speech synthesis -
- Theme-3
  - A new framework for “human-like” speech machines #1
  - A new framework for “human-like” speech machines #2
  - A new framework for “human-like” speech machines #3
  - A new framework for “human-like” speech machines #4



Phones and phonemes

- Phones
  - A phone is the minimal unit of speech of any language.
  - Phonetic symbols are language-independent and used by phoneticians to transcribe speech of any language. Defined by by Int. Phonetic Association.
  - Should be used like [a b c d e f g].



Dental	Alveolar	Postalveolar	Retroflex
t	d		ʈ ɖ
	n		ɳ

- Phonemes
  - A phoneme is the minimal unit of speech of a specific language, perceived by native speakers of that language.
  - Phonemic symbols are language-dependent and used by ordinary people to transcribe speech of that language. Can be defined by a user.
  - Should be used like / a b c d e f g /.

/arajurugeNzituo/ → [ɐrɐjɨrɨgɐ̃ɐ̃ɲd̪ʑit̪sɨo̞ʔ]

Phones and phonemes

- Sounds of a class can be perceived as sounds of different classes.
  - とんぼ，とんねる，どんぐり [m], [n], [ŋ]
  - ライト，ライト right, light
  - すいか，たべますか？ [sɯ], [s]
    - For Japanese, they are of one class but for foreigners, they may be of different classes.
    - Japanese may have less capacity of phone discrimination but they may have better capacity of discriminating sounds by their duration.
      - おばさん，おばあさん，　おかやま（岡山），おおかやま（大加山），おおおかやま（大岡山）
- Phonemes and allophones
  - One phoneme is sometimes acoustically realized as different phones.
  - ん → [m], [n], [ŋ] [m], [n], and [ŋ] are allophones of ん.
- Phones are objective(acoustic) and phonemes are subjective(mental)?
  - #phones >> #phonemes (30 -- 40). Phones are finer units of speech.
  - Definition of phones is still based on speakers' abstraction of speech acoustics.
    - The definition does not discriminate between adults' [a] and kids' [a] although their spectral envelopes are very different between them.

Speech Communication Tech.

- Acoustic analysis of speech -

Nobuaki Minematsu

Web-based speech analyzer

https://www.speechandhearing.net/talk/tools/#/

Today's menu

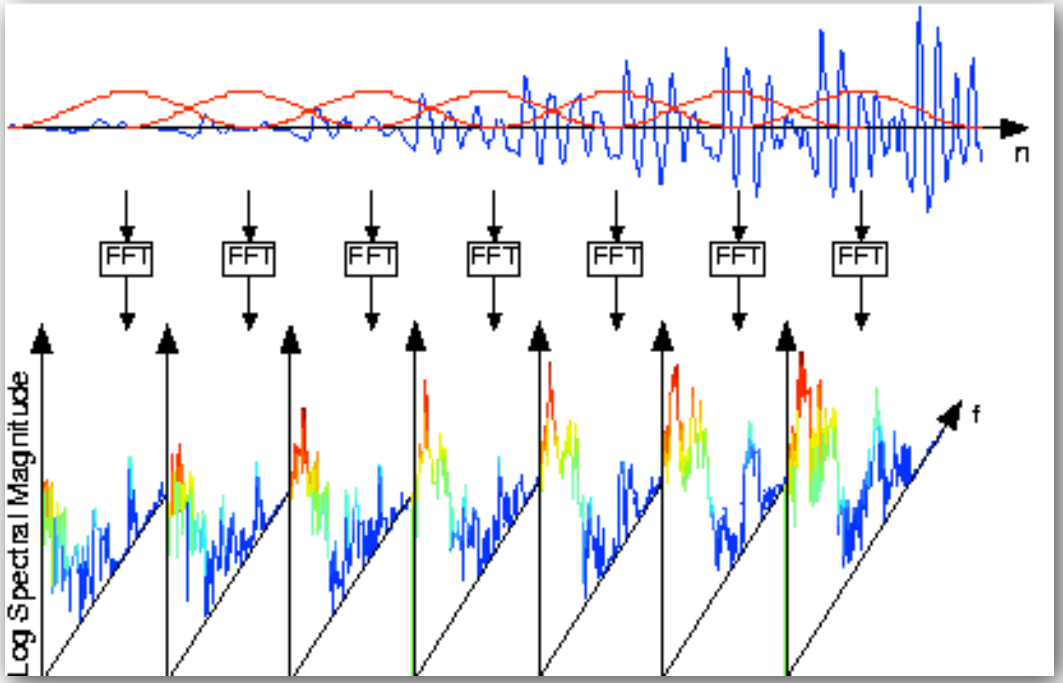
- More on details of acoustic phonetics (continued)
  - Characteristics of human hearing
  - Fundamental frequency and pitch again
  - Fourier analysis of speech signals
  - Simple hearing tests

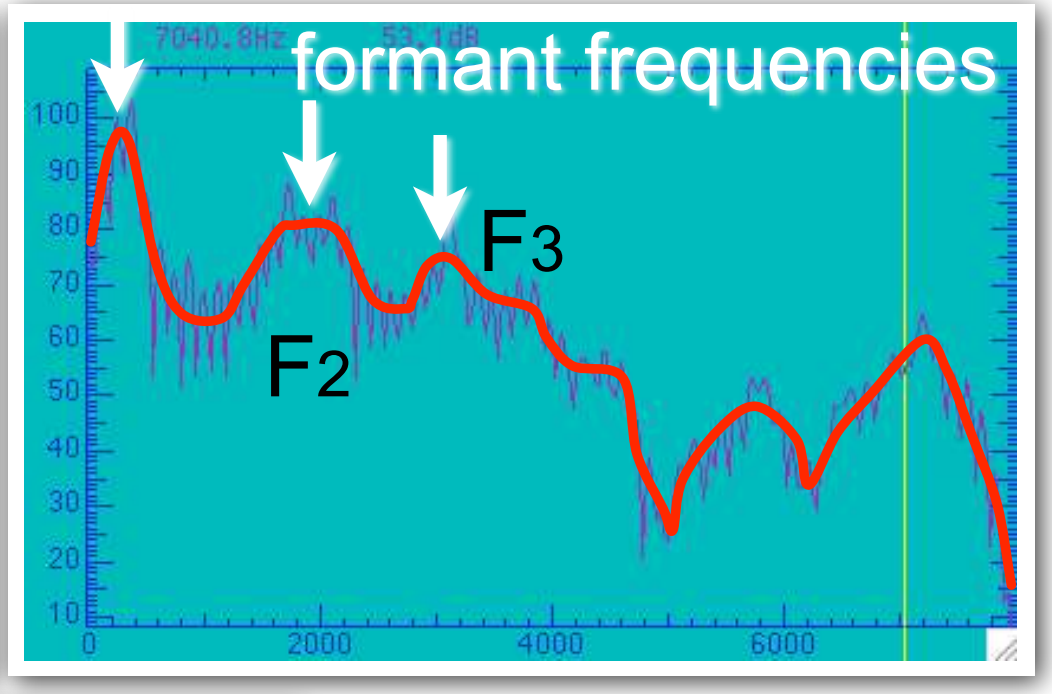
- Technology for acoustic analysis of speech
  - Source-filter model of speech production $S(\omega) = G(\omega)H(\omega)R(\omega)$
  - Cepstrum method to separate source and filter
  - Advanced analysis tool of STRAIGHT
  - Some morphing examples
  - LPC, PARCOR, and the shape of a vocal tube

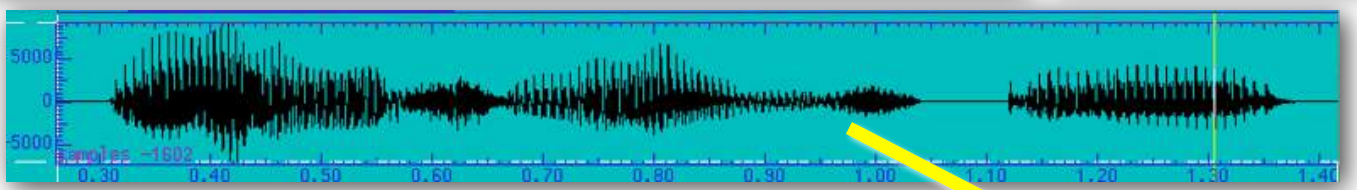
- Spectrums/waveforms of various language sounds
  - Vowels, semivowels, liquids, nasals, voiced fricatives, unvoiced fricatives, glottals,
  - voiced plosives, unvoiced plosives, voiced affricatives, and unvoiced affricatives
  - Speech recognition as spectrum reading
- Summary

Acoustic phonetics

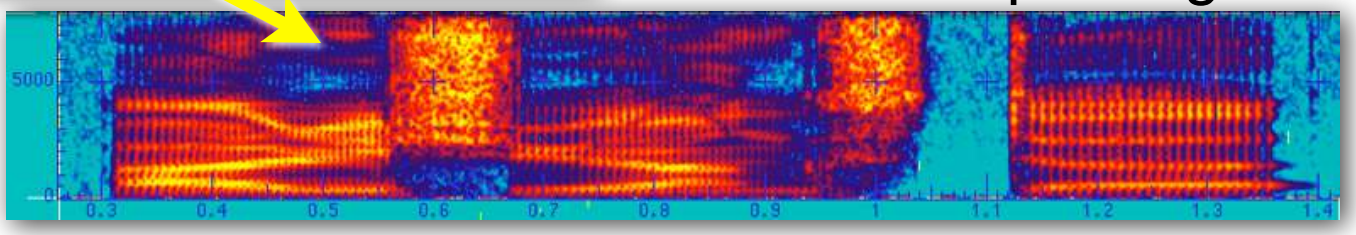
- From waveforms to spectrums
  - Windowing + FFT + log-amplitude





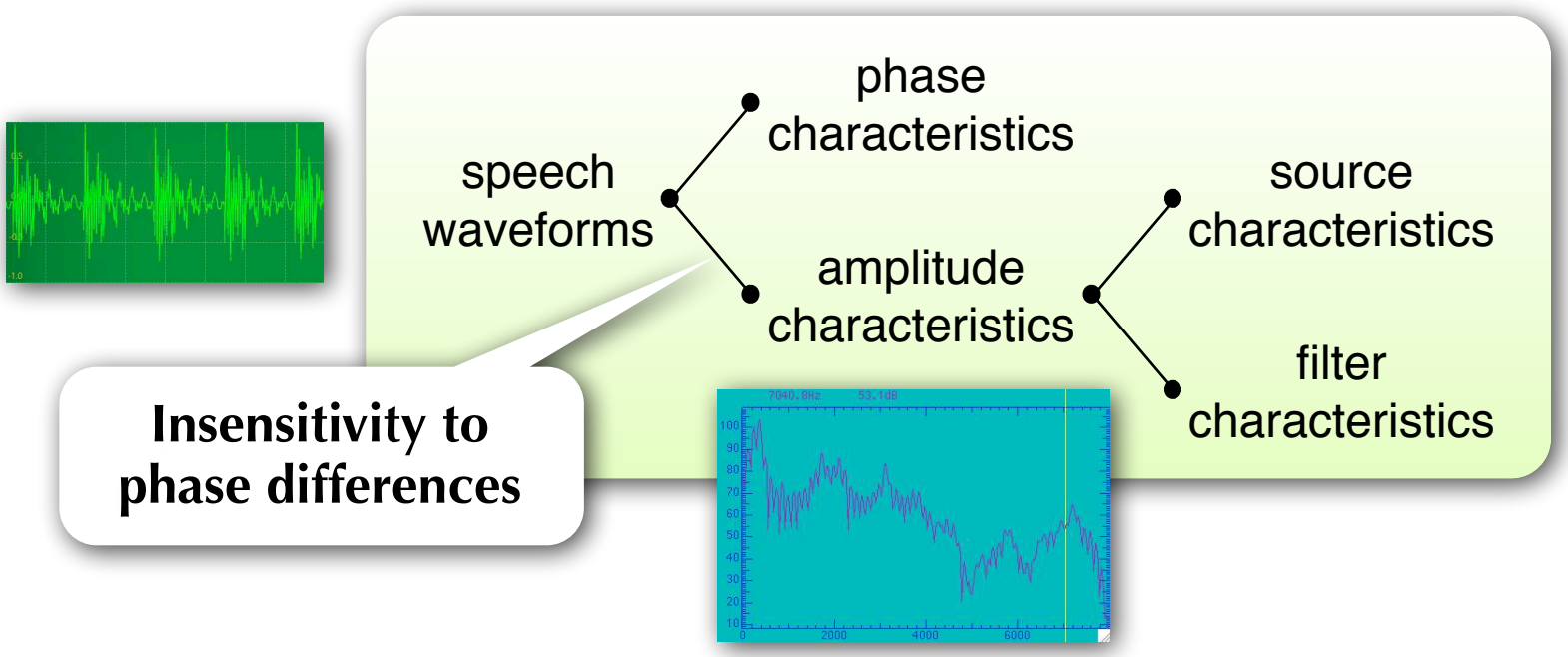


spectrogram



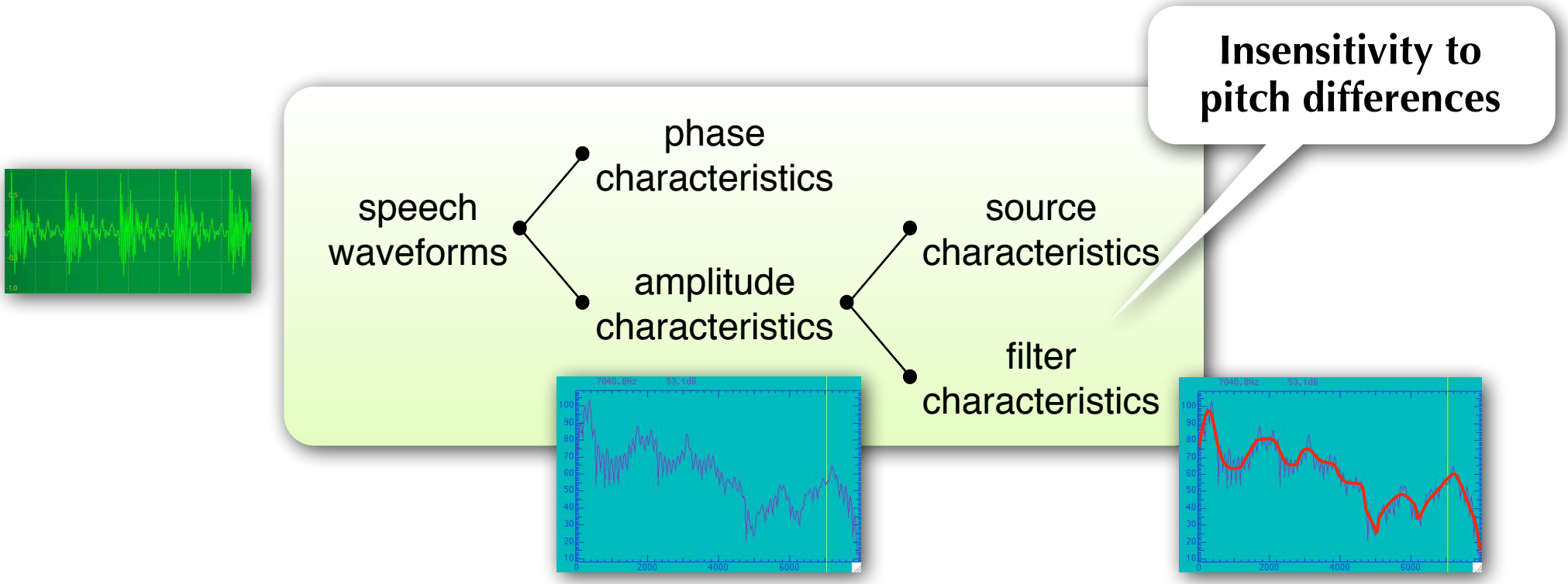
Waveform to spectrum

- From waveforms to spectrums
  - Windowing + FFT + log-amplitude
- Insensitivity of human ears to phase characteristics of speech
  - Human ears are basically "deaf" to phase differences in speech.
  - It is not impossible for us to discriminate acoustically two sounds with different phase characteristics but we don't discriminate them linguistically.
    - No language treats those two sounds as two different *phonemes*.



Spectrum to spectrum envelope

- From spectrums to spectrum envelopes
  - log-amplitude spectrum -> smoothing -> spectrum envelope
- Humans' insensitivity to pitch differences when perceiving phonemes.
  - /a/ with high tone and /a/ with low tone are perceived to be of the same class.
  - Separation of pitch (fundamental frequency) can be done by spectrum smoothing.



Speech waveforms and pitch

- /a/ (low) --> /a/ (middle) --> /a/ (high)

T_0
fundamental period

$F_0 = 1/T_0$ fundamental frequency

Speech spectrums and pitch

- /a/ (low) --> /a/ (middle) --> /a/ (high)

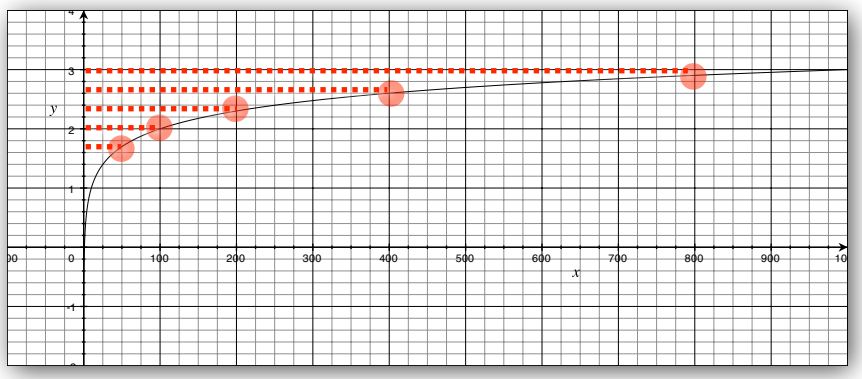
1 octave = doubled F_0

- Mathematical mechanism of music (scale)

C→C#→D→D#→E→F→F#→G→G#→A→A#→B→C

$\times 1.059$ $\times 1.059$ $\times 1.059$ $\times 1.059$ $\times 2.0$

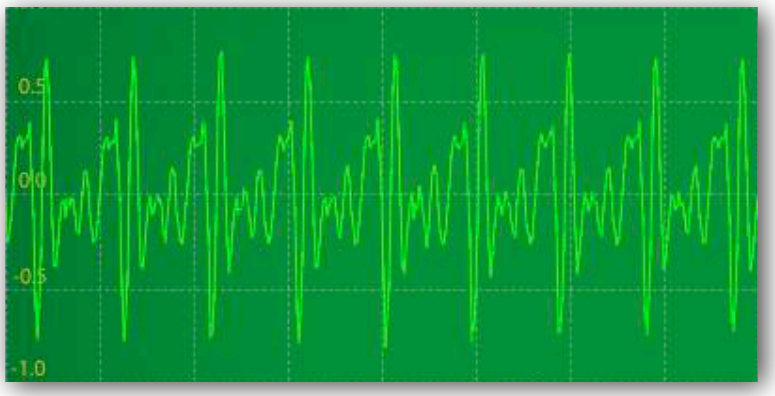
$$1.059 = 2^{\frac{1}{12}}$$

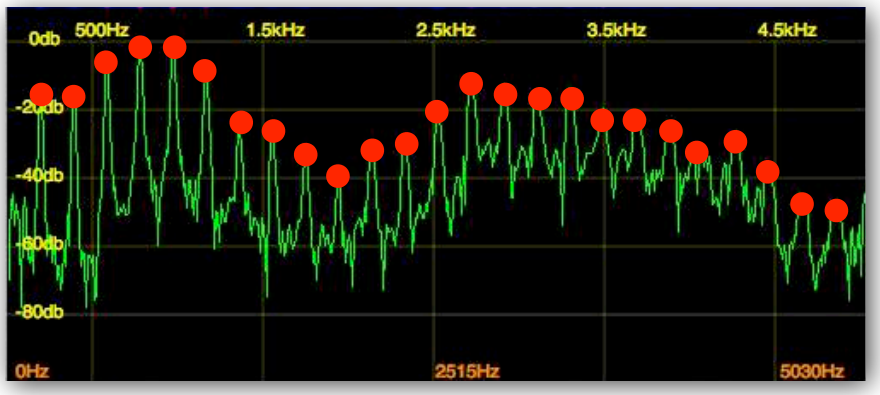


$$y = \log_{10}(x)$$

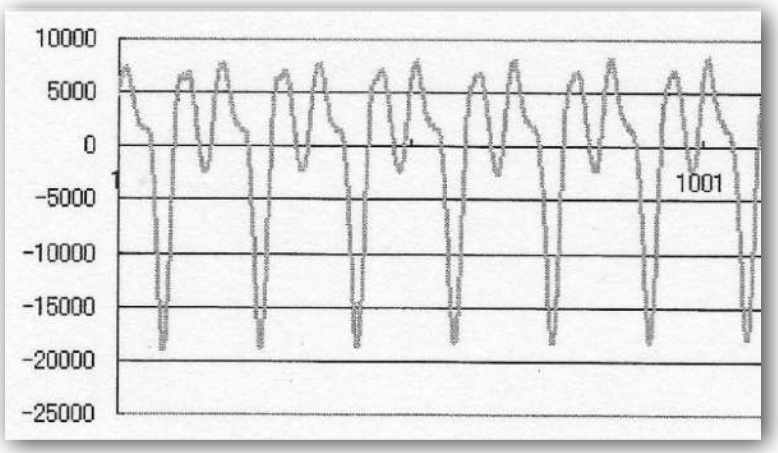
Harmonic structure

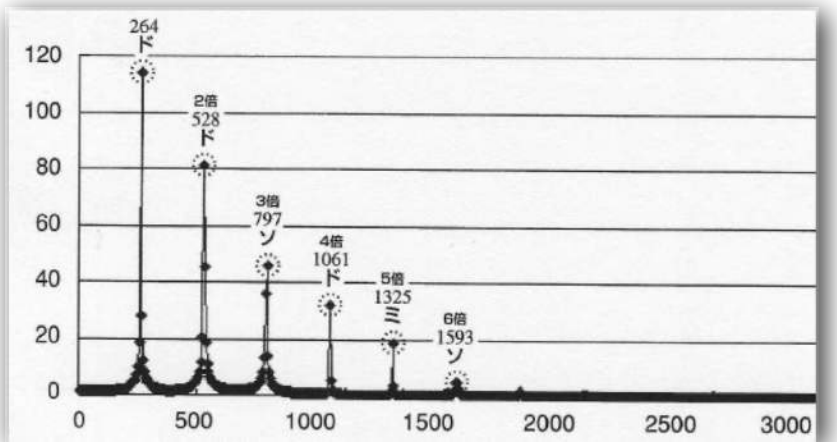
- Speech waveforms and their log power spectrum





- Guitar sound waveforms and their linear power spectrum

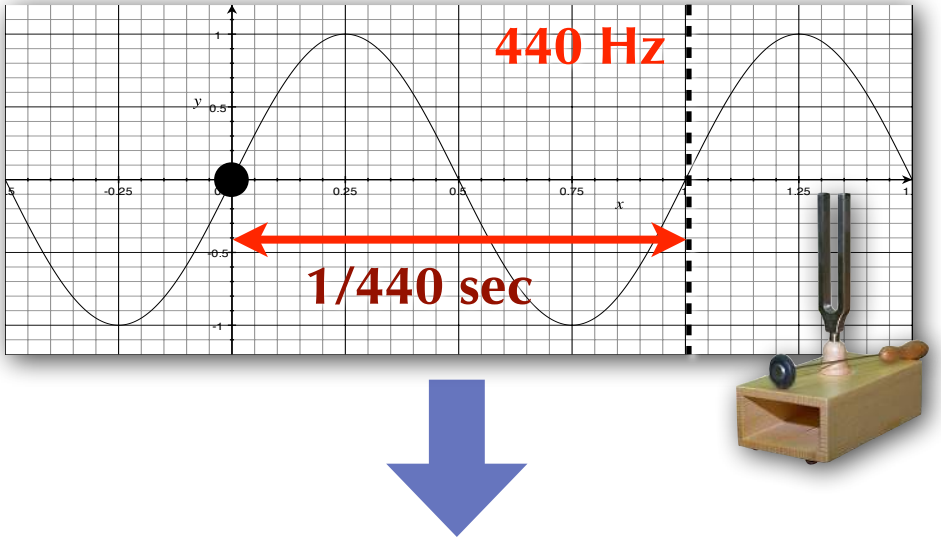


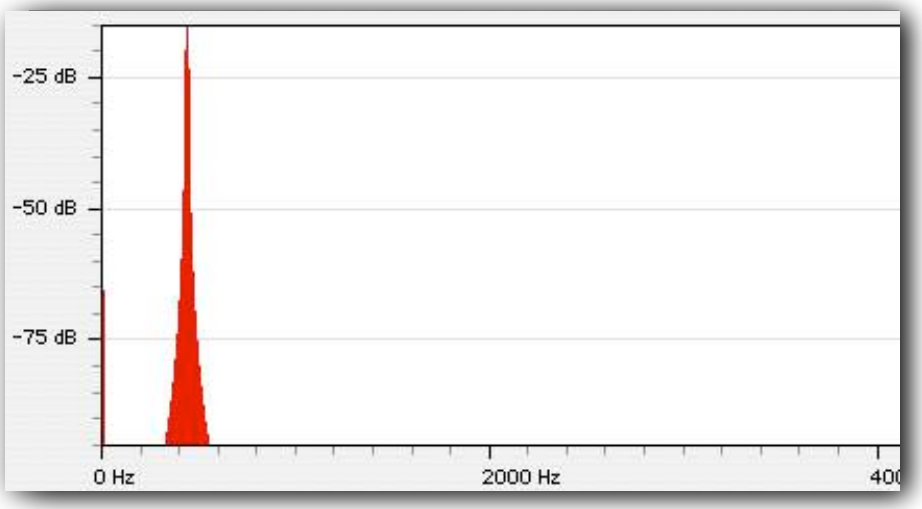


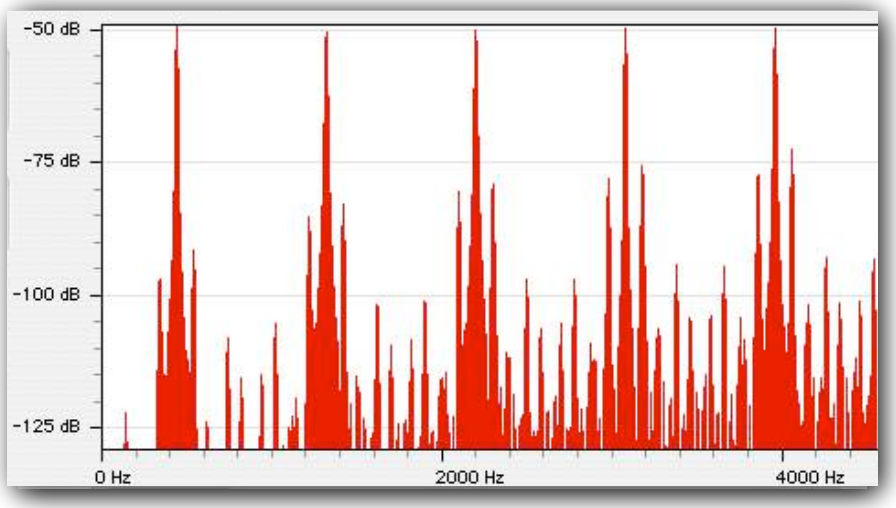
  - Fundamental tone + 2nd harmonic + 3rd harmonic + ...
    - Fourier series of periodic signals -> Results (spectrums) also become periodic.

Harmonic structure

- Pure tone and complex tone
  - Waveforms and their linear/log power spectrum

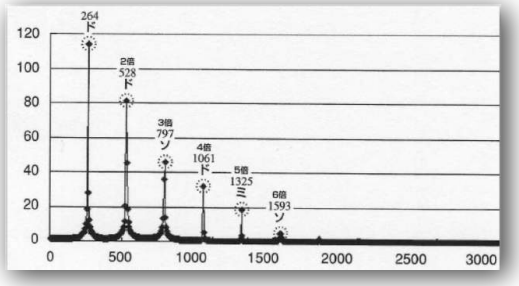






Fourier series and speech production

- Periodic signals are decomposed into $\sum$ sinusoidal waveforms
  - Periodic signals have a set of line spectrums.

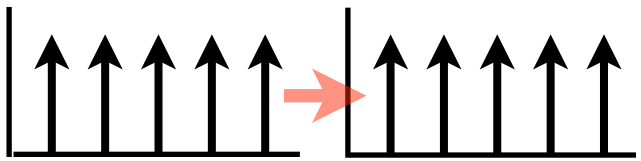


- Fourier series of a train of impulses
  - A train of impulses

    $g(t) = \sum_{k=-\infty}^{\infty} \delta(t - kT_0)$
  - Fourier series of a train of impulses

    $g(t) = \sum_{n=-\infty}^{\infty} \alpha_n e^{jn\omega_0 t}$

    $\alpha_n = \frac{1}{T_0} \int_{-\frac{T_0}{2}}^{\frac{T_0}{2}} g(t) e^{-jn\omega_0 t} dt = \frac{1}{T_0} \int_{-\frac{T_0}{2}}^{\frac{T_0}{2}} \delta(t) e^{-jn\omega_0 t} dt = \frac{1}{T_0}$

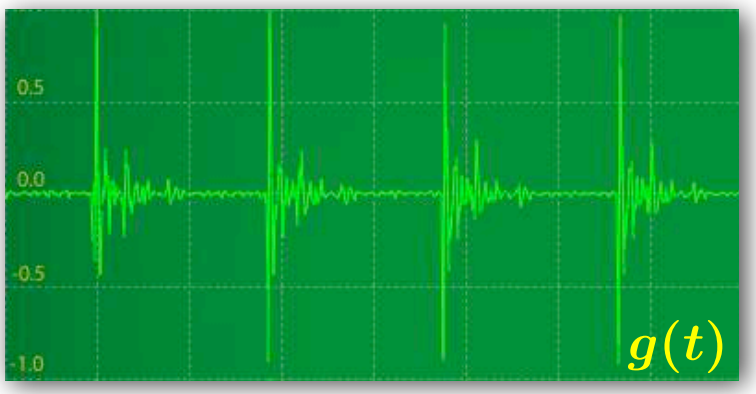


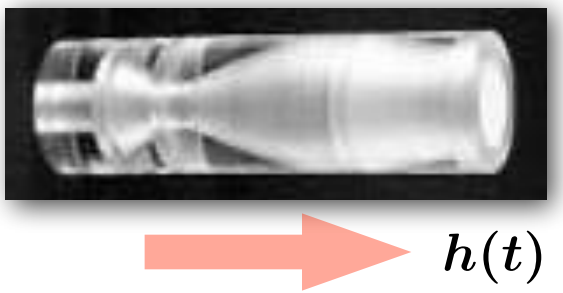
  - Fourier transform of a train of impulses

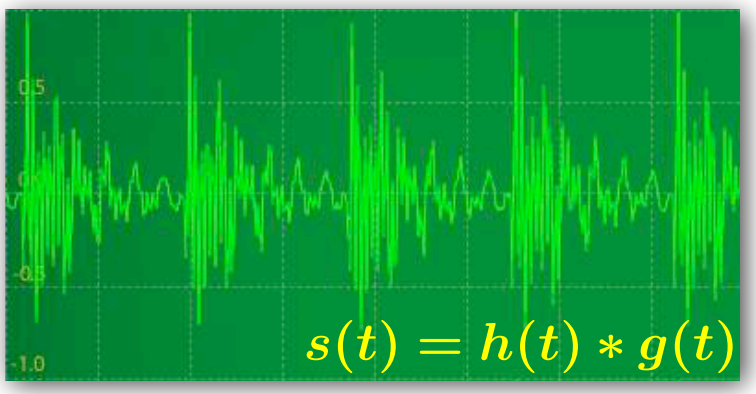
    $G(\omega) = \frac{1}{T_0} \sum_{n=-\infty}^{\infty} \int_{-\infty}^{\infty} \left\{1 \times e^{jn\omega_0 t}\right\} e^{-j\omega t} dt = \frac{2\pi}{T_0} \sum_{n=-\infty}^{\infty} \delta(\omega - n\omega_0)$
- Vowel production as convolution of impulse response
  - Vocal tract (tube) functions as a filter : impulse response of $h(t)$
  - Glottal source waveform : $g(t)$, output waveform : $s(t)$
- $s(t) = h(t) * g(t)$

Acoustic phonetics

- Spectrum of a vowel sound



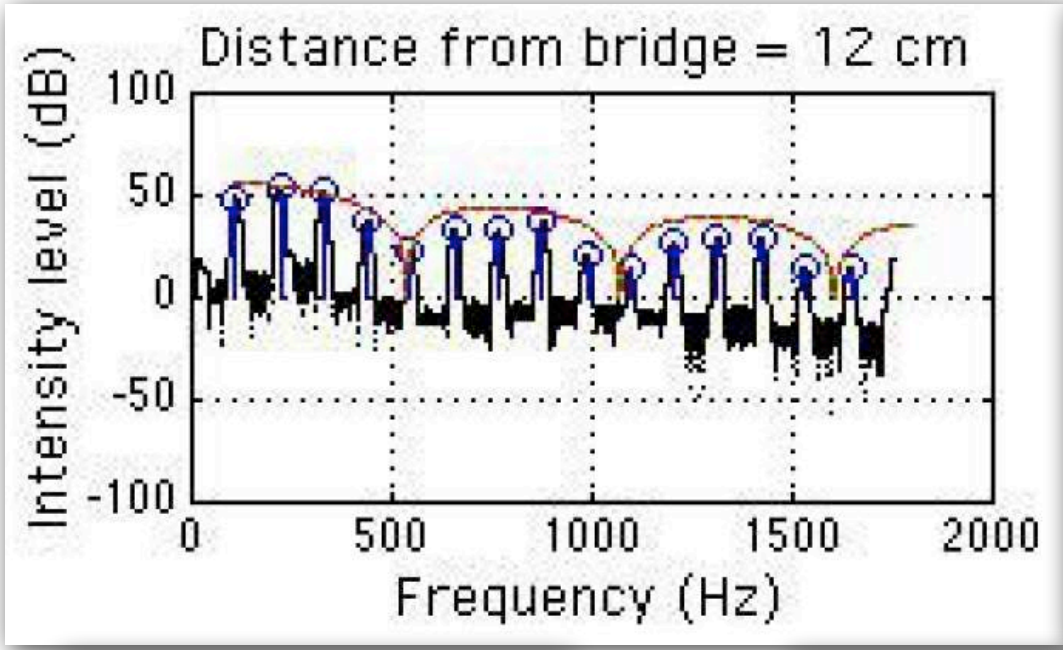


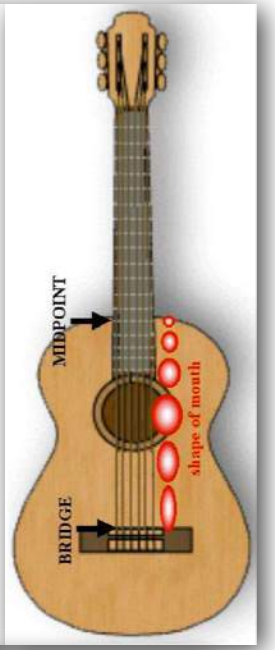


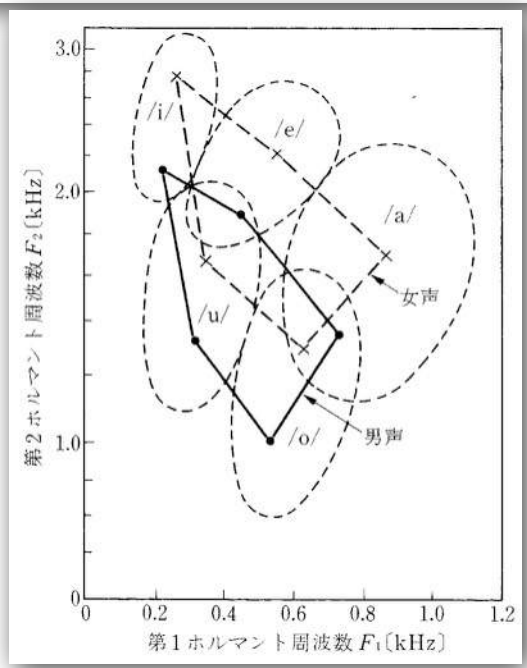
Resonance = concentration of the energy on specific bands that are determined only by the shape of a tube used for sound generation.

Timbre = energy distribution pattern over the frequency axis

Spectrum analysis of guitar sounds







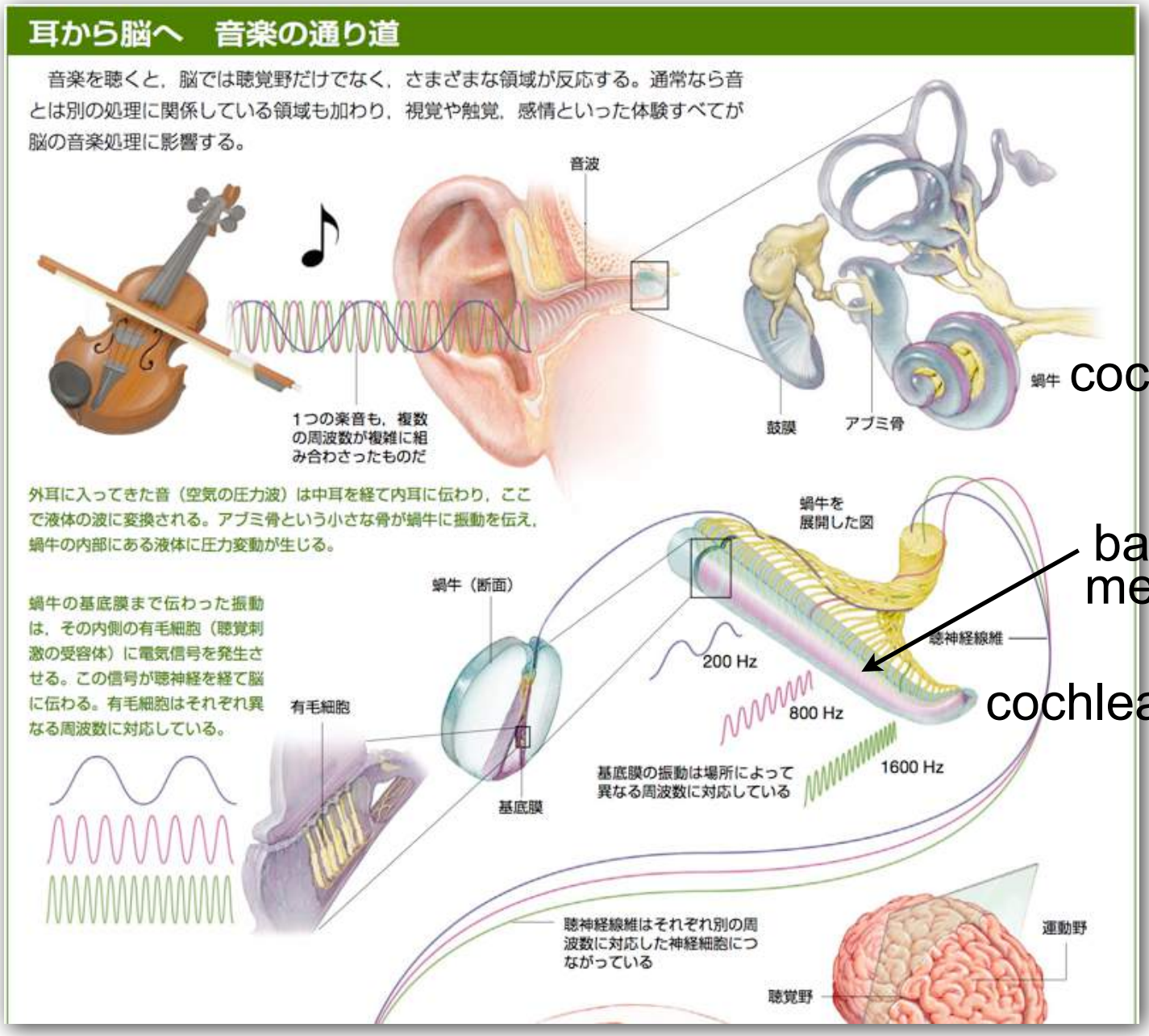
oboe

English horn

bassoon

flute

How sounds are processed in the ears



cochlea

basement membrane

cochlea

Ear = Fourier analyzer

- Frequency of activation of each band of the cochlea

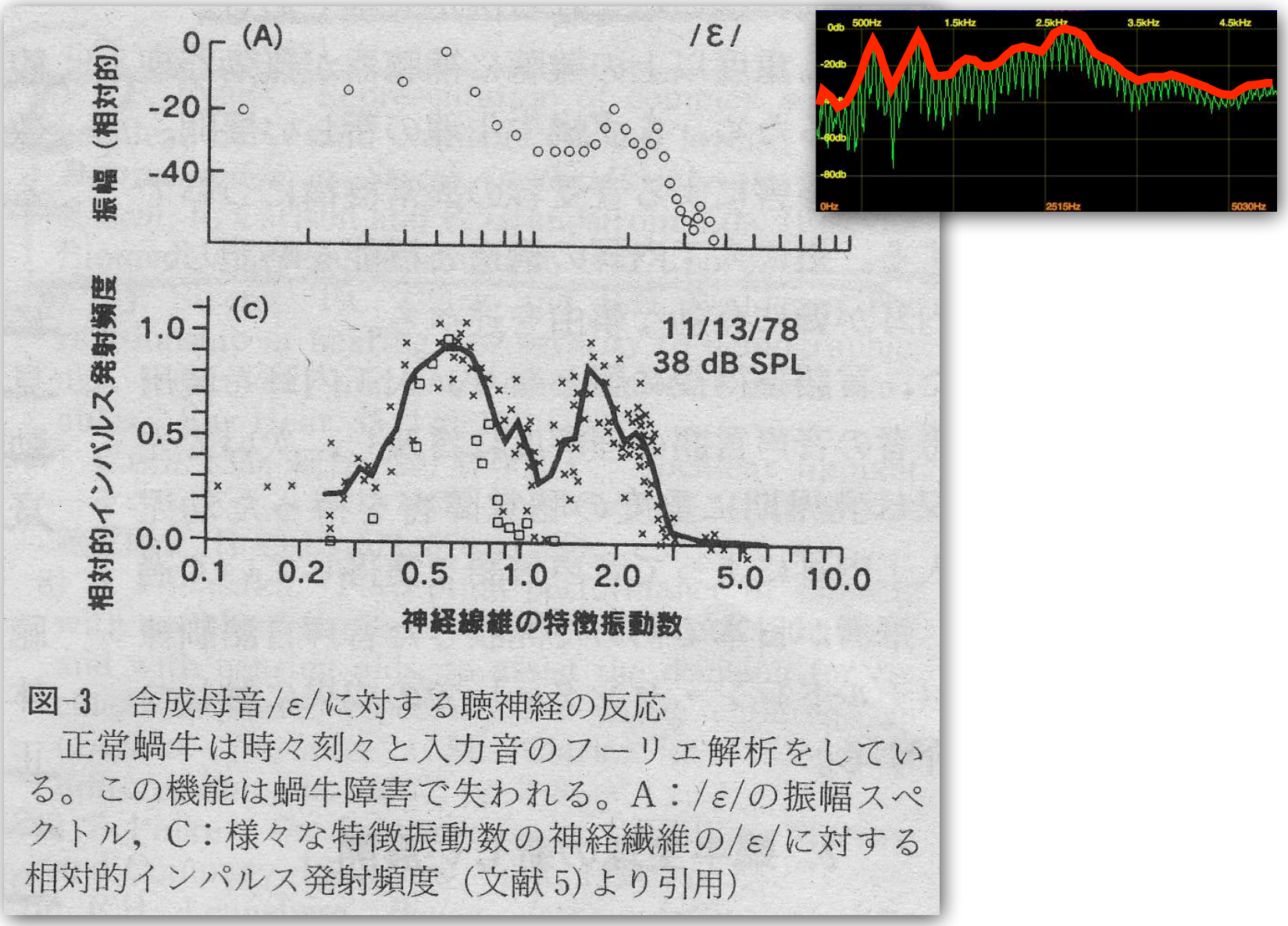
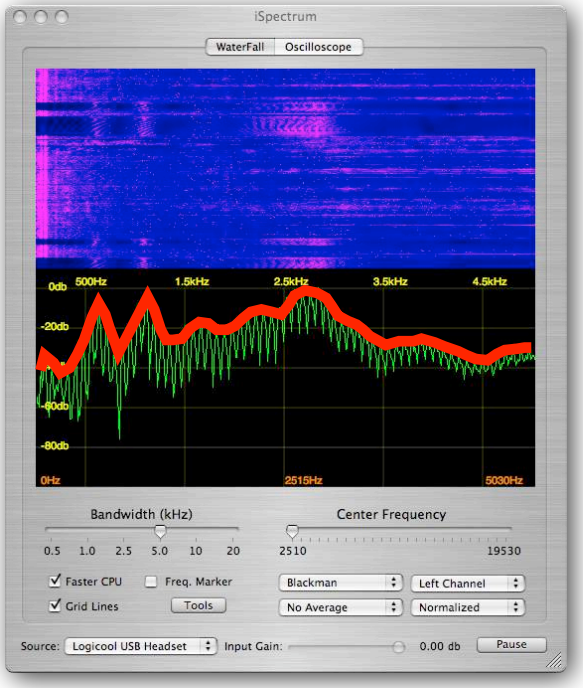


図-3　合成母音/ε/に対する聴神経の反応
正常蝸牛は時々刻々と入力音のフーリエ解析をしている。この機能は蝸牛障害で失われる。A：/ε/の振幅スペクトル，C：様々な特徴振動数の神経繊維の/ε/に対する相対的インパルス発射頻度（文献5)より引用）

Speech = vibrations of air particles

- The four aspects of tones (sounds)
  - Height of tones (pitch of tones)
    - High tones and low tones
  - Loudness of tones
    - Loud tones and soft tones
  - Duration of tones
    - Long tones and short tones
  - Timbre of tones (color of tones, 音色, 声色)
    - ????
    - If two tones have the same height, the same loudness, and the same duration but the two tones are perceived as different tones, then, the two tones differ in their timbre.
    - /a/ and /i/ /a/ and /a/
      - difference in phoneme, difference in gender



Timbre = energy distribution pattern over the frequency axis

Determined only by the shape of a tube used for sound generation

Hearing test 1

- Q : what kind of *acoustic* change is expected when a vocal tube becomes shorter?

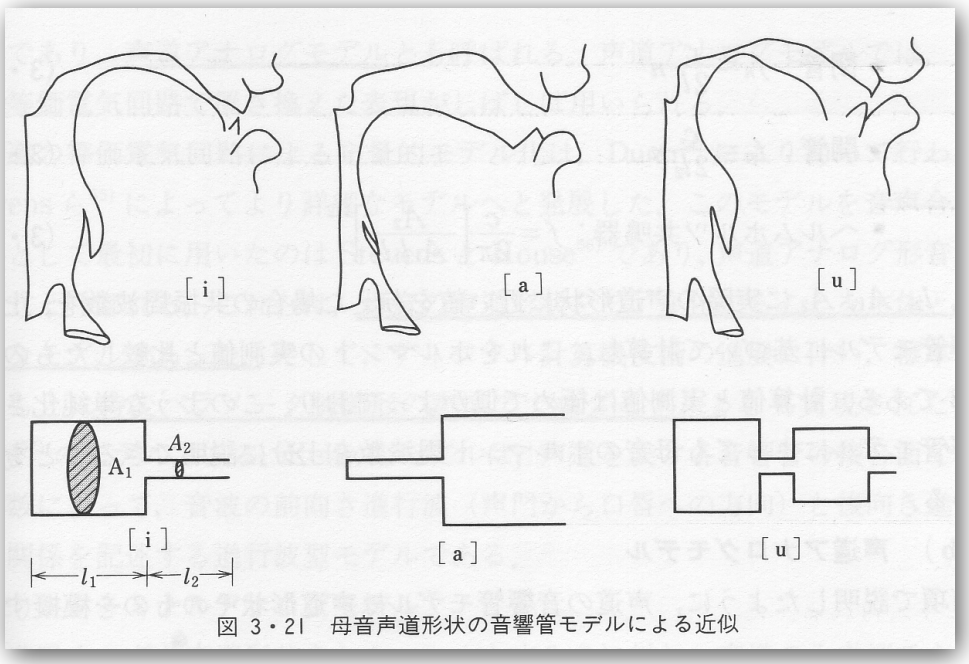


図 3・21　母音声道形状の音響管モデルによる近似

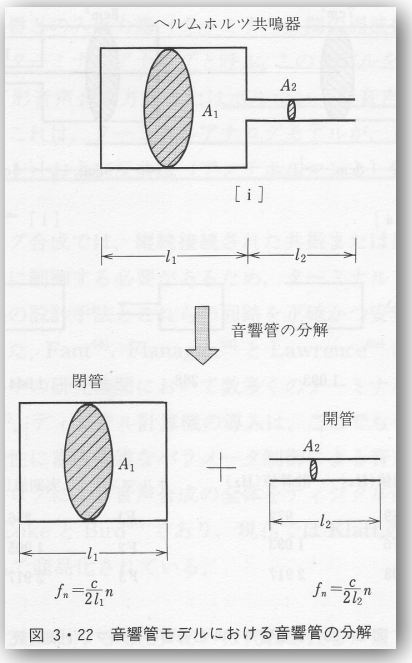


図 3・22　音響管モデルにおける音響管の分解

$$f_n = \frac{c}{2l_1}n$$

$$f_n = \frac{c}{2l_2}n$$

$$f = \frac{c}{2\pi}\left[\frac{A_2}{A_1 l_1 l_2}\right]^{1/2}$$

A → B → C

Replay

Hearing test 2

- Q : Guess what kind of *tube shape* change happened by hearing the sounds before and after the tube shape change.

A =

A → B B → A

Replay

Hearing test 2

- Q : Guess what kind of tube shape change happened by hearing the sounds before and after the tube shape change.

Today's menu

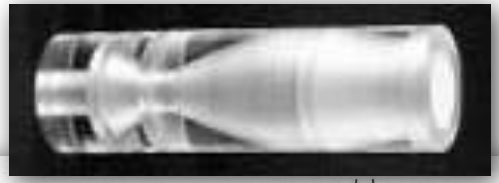
- More on details of acoustic phonetics (continued)
  - Characteristics of human hearing
  - Fundamental frequency and pitch again
  - Fourier analysis of speech signals
  - Simple hearing tests

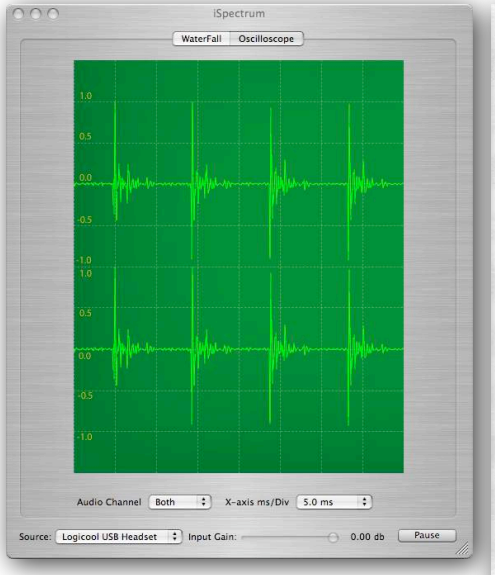
- Technology for acoustic analysis of speech
  - Source-filter model of speech production $S(\omega) = G(\omega)H(\omega)R(\omega)$
  - Cepstrum method to separate source and filter
  - Advanced analysis tool of STRAIGHT
  - Some morphing examples
  - LPC, PARCOR, and the shape of a vocal tube

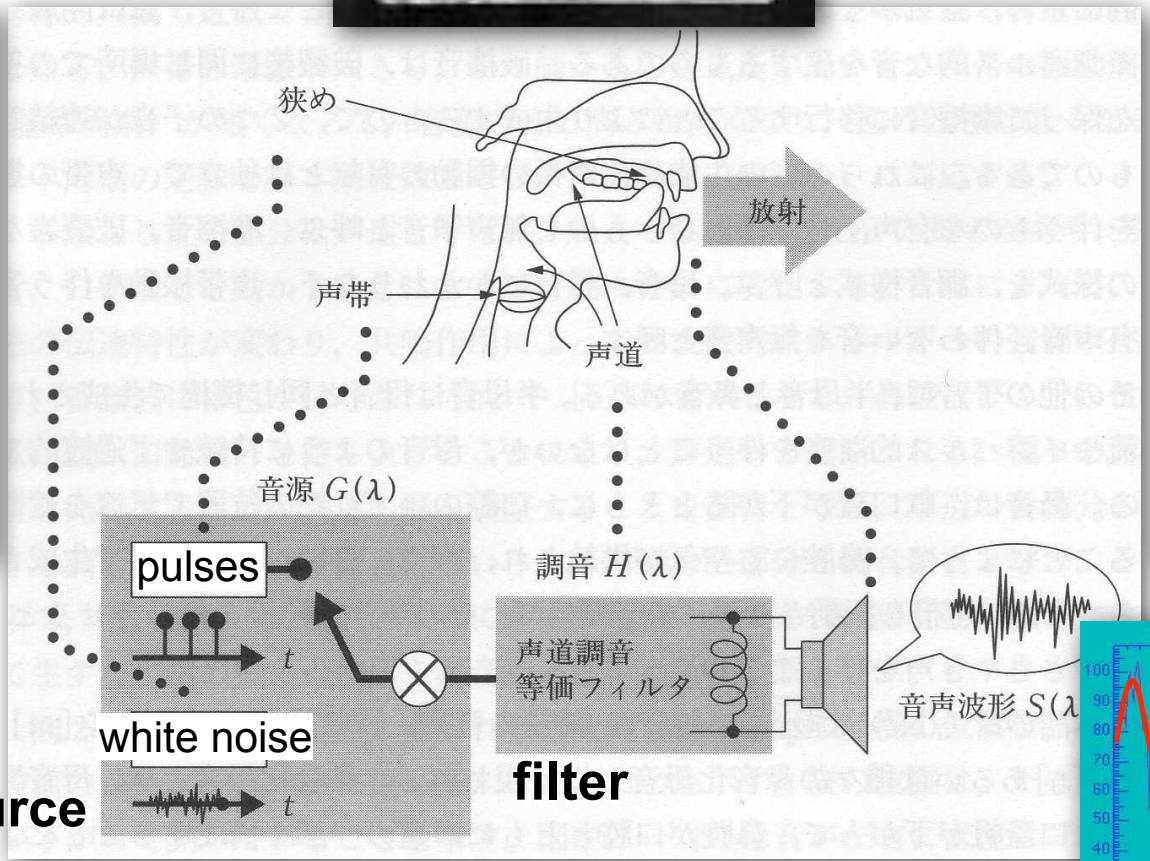
- Spectrums/waveforms of various language sounds
  - Vowels, semivowels, liquids, nasals, voiced fricatives, unvoiced fricatives, glottals,
  - voiced plosives, unvoiced plosives, voiced affricatives, and unvoiced affricatives
  - Speech recognition as spectrum reading
- Summary

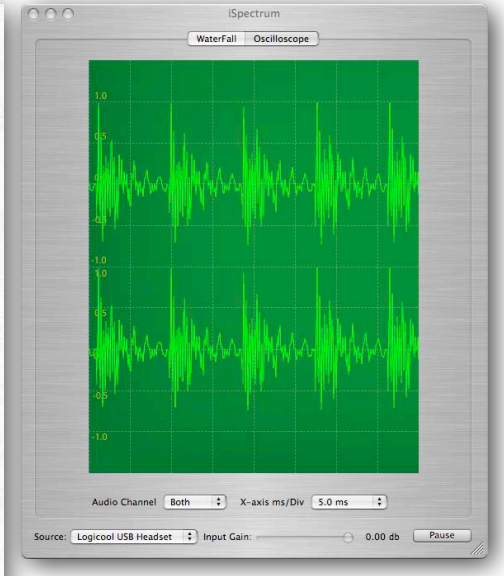
Modeling of speech production

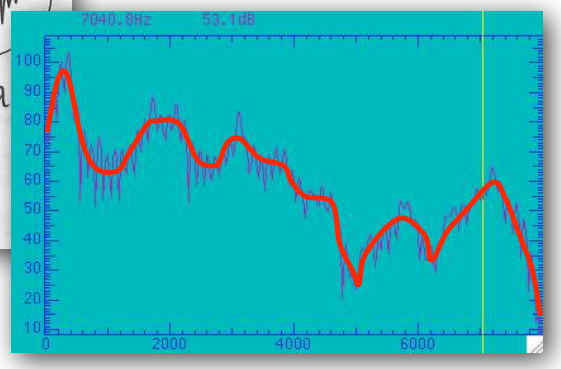
- Mathematical modeling of speech production -- source & filter model --
  - Linear independence between source and filter







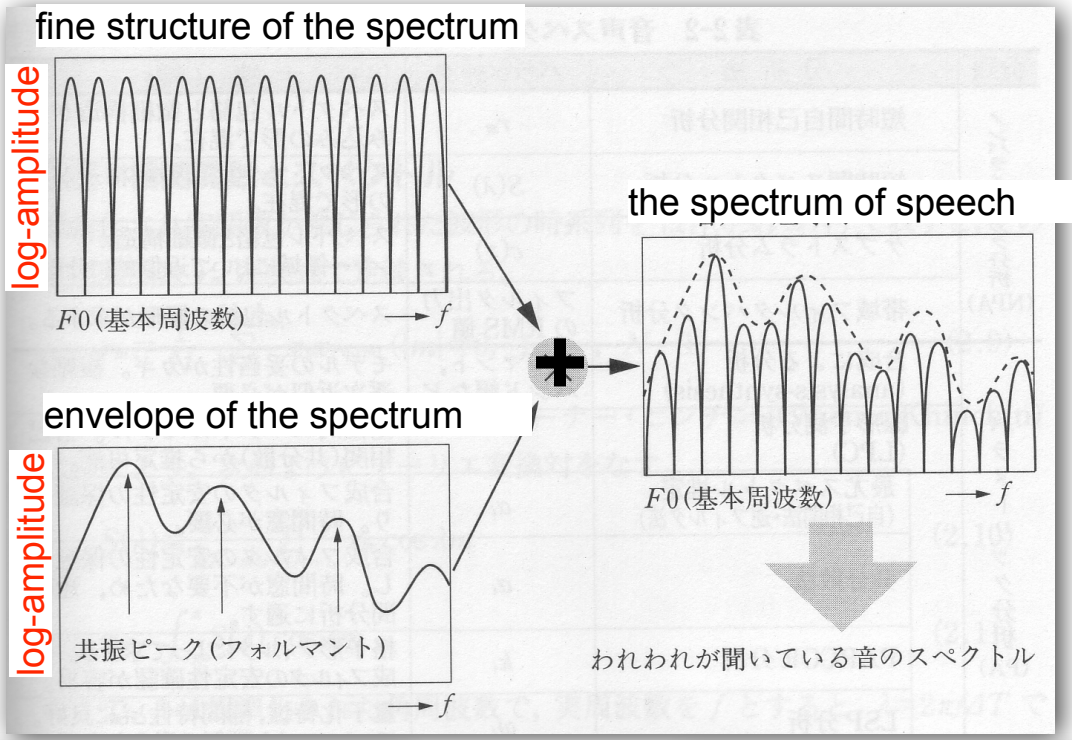


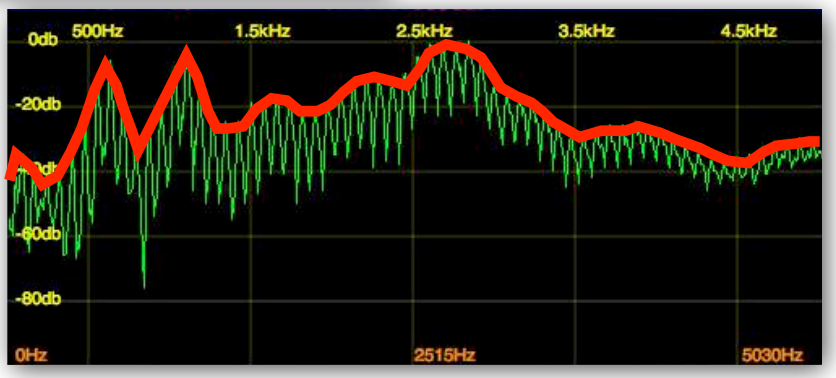


$$S(\omega) = G(\omega)H(\omega)R(\omega)$$

Modeling of vowel production

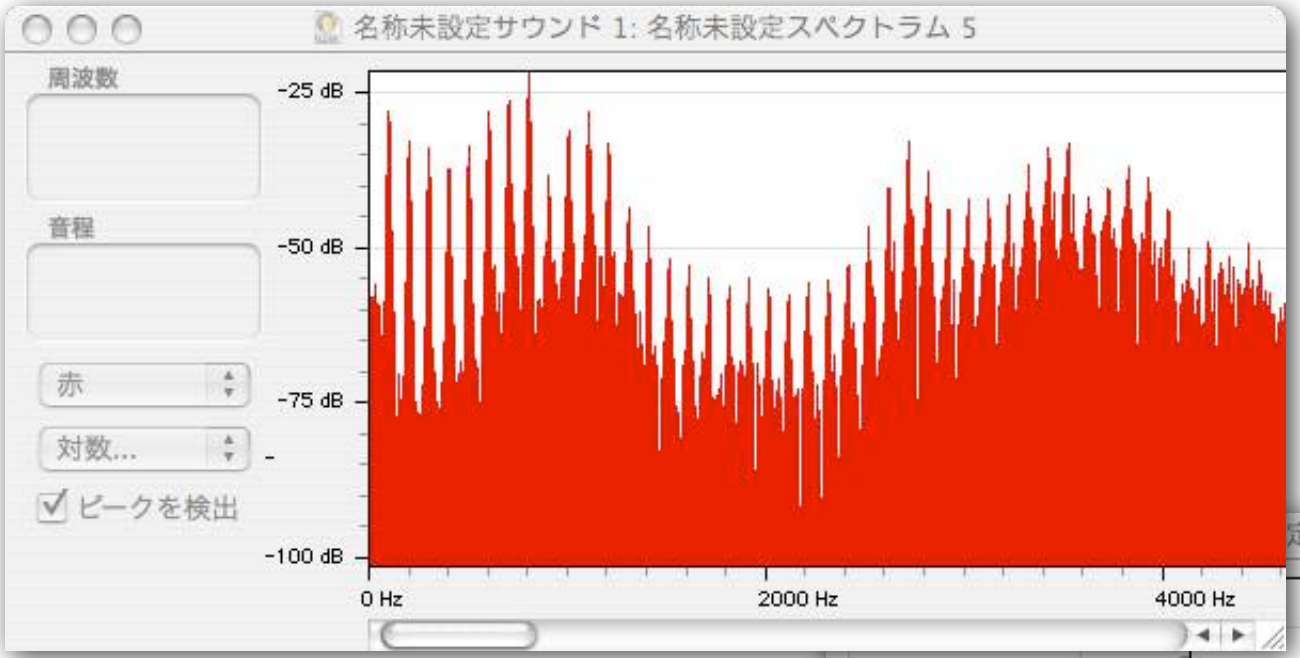
- Mathematical modeling of speech production -- source & filter model --
  - Separation between the spectrums of source and filter

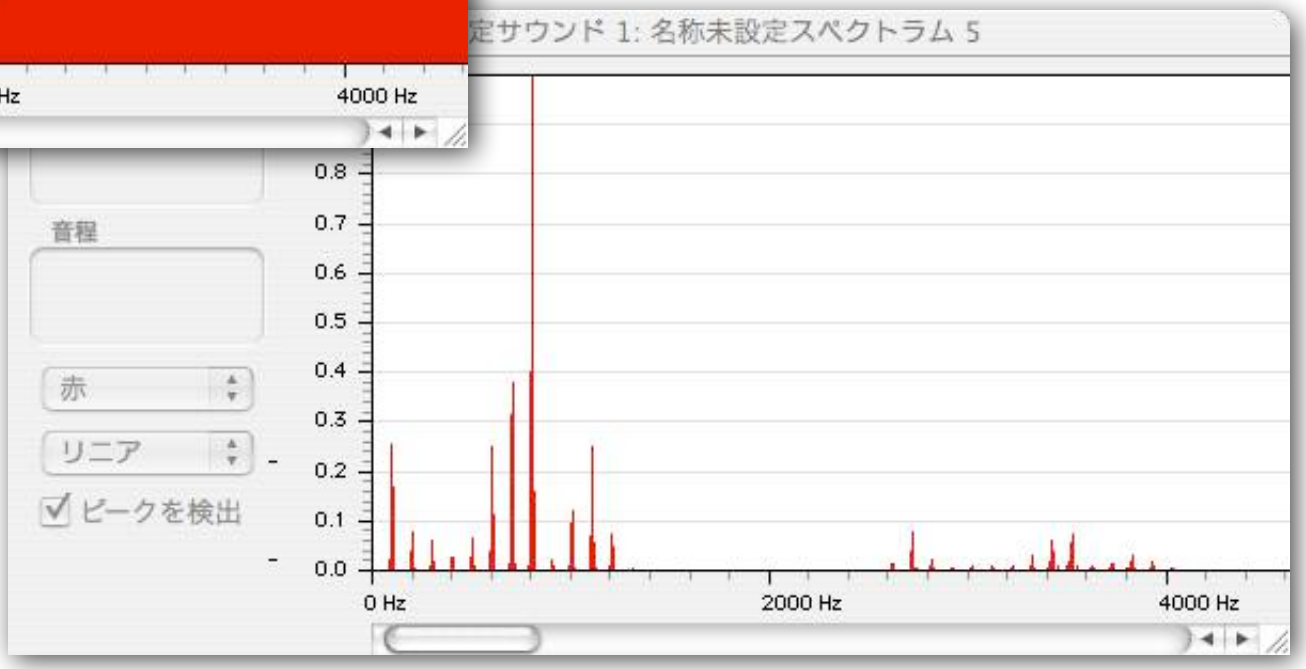




A comment on linear and log spectrums

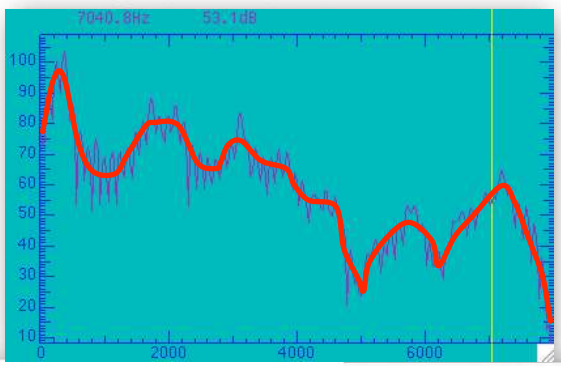
- Their appearances are very different.

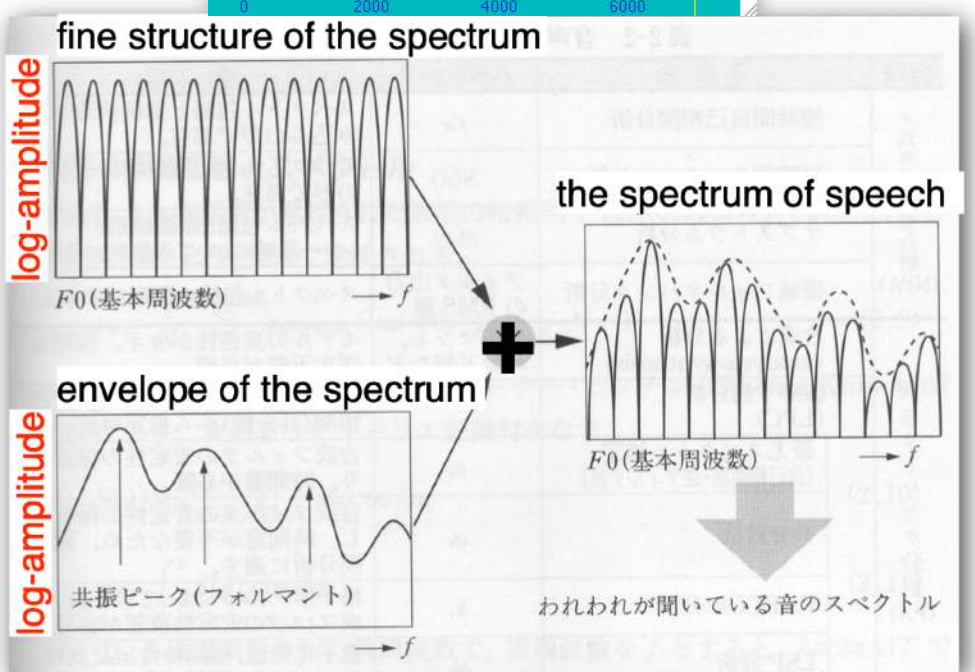


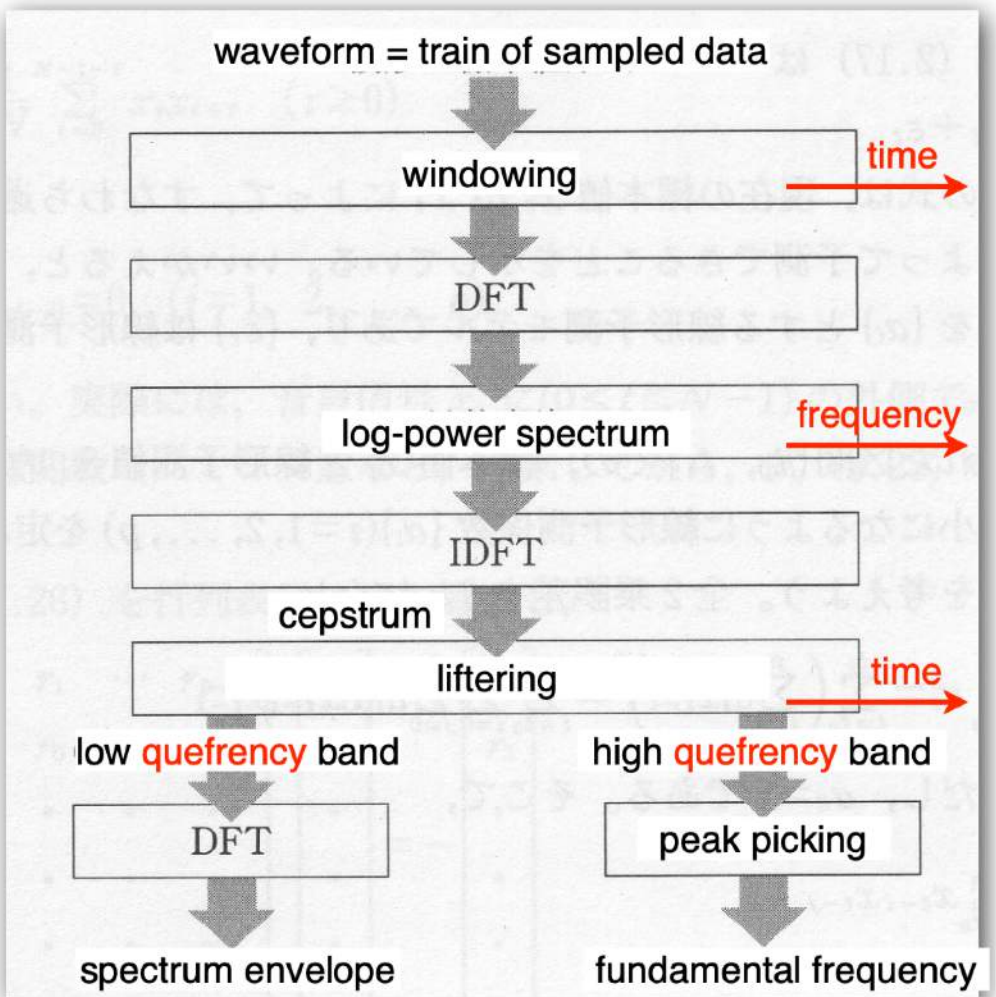


Extraction of spectrum envelopes

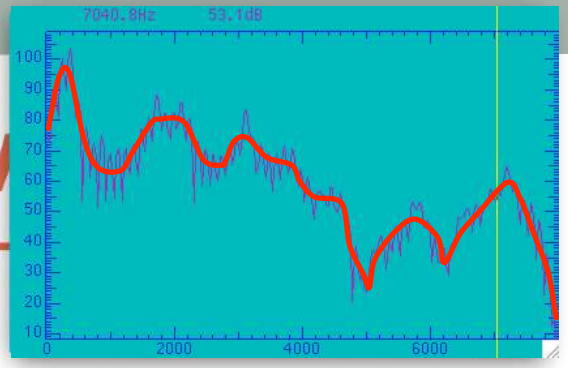
- Cepstrum method
  - Windowing + FFT + log-amplitude --> a spectrum with pitch harmonics
  - Smoothing (LPF) of the fine spectrum into its smoothed version







Extraction of spectrum env



- Cepstrum method
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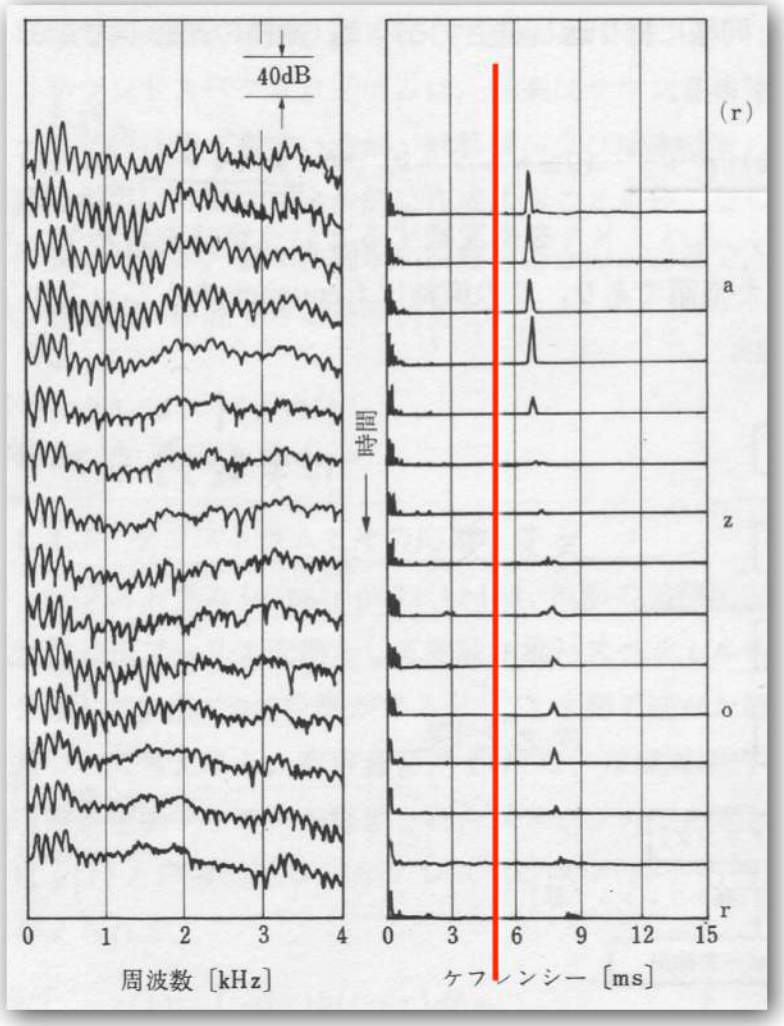
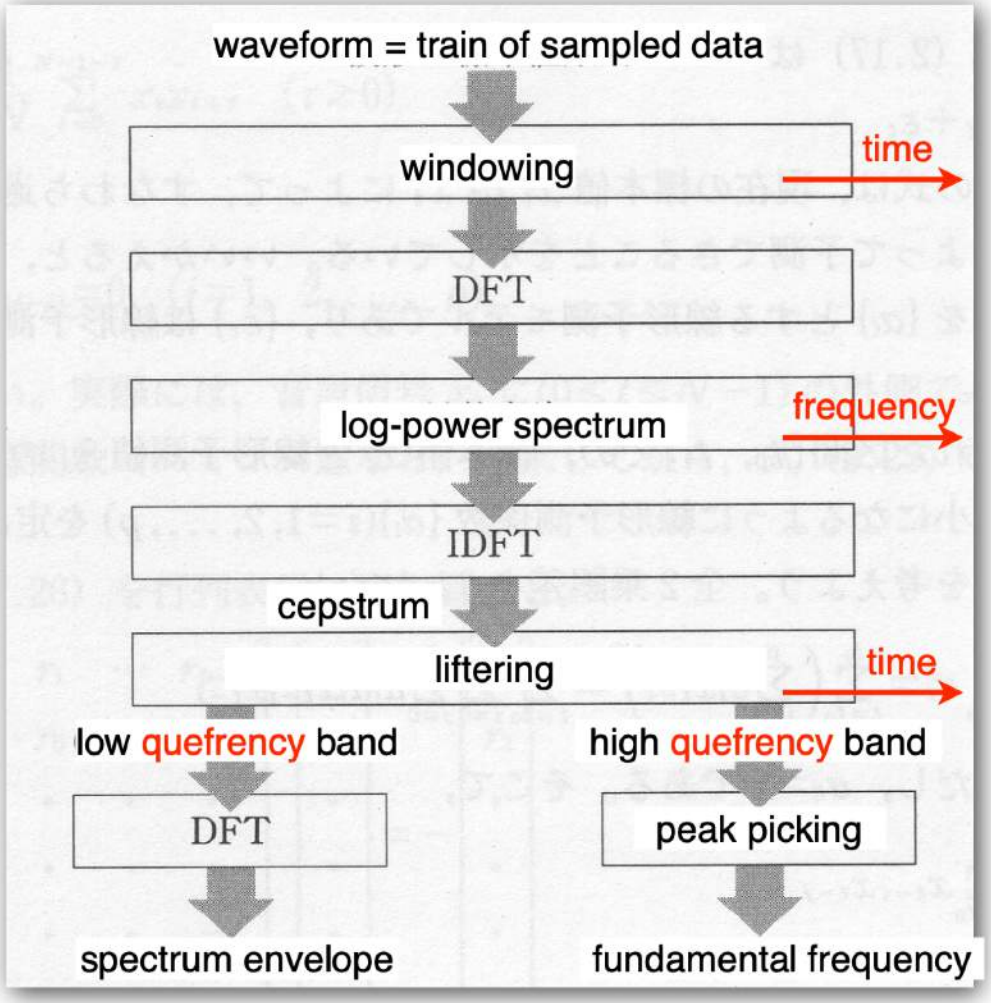
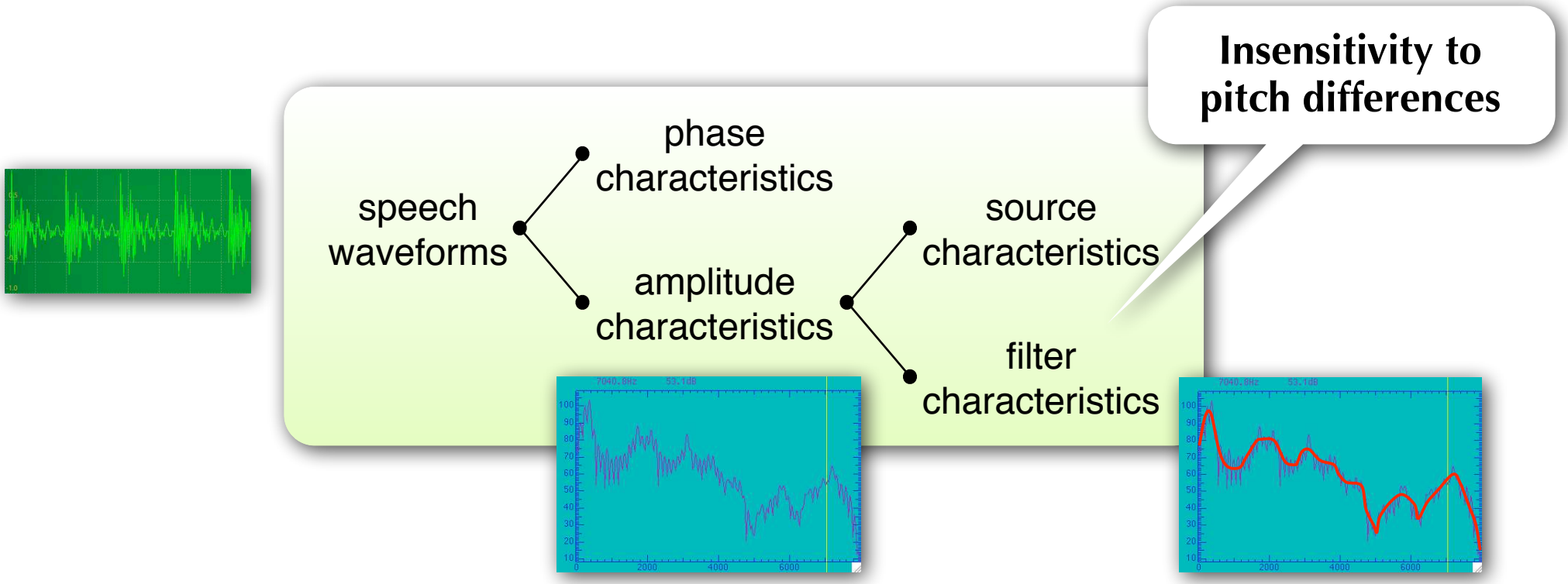




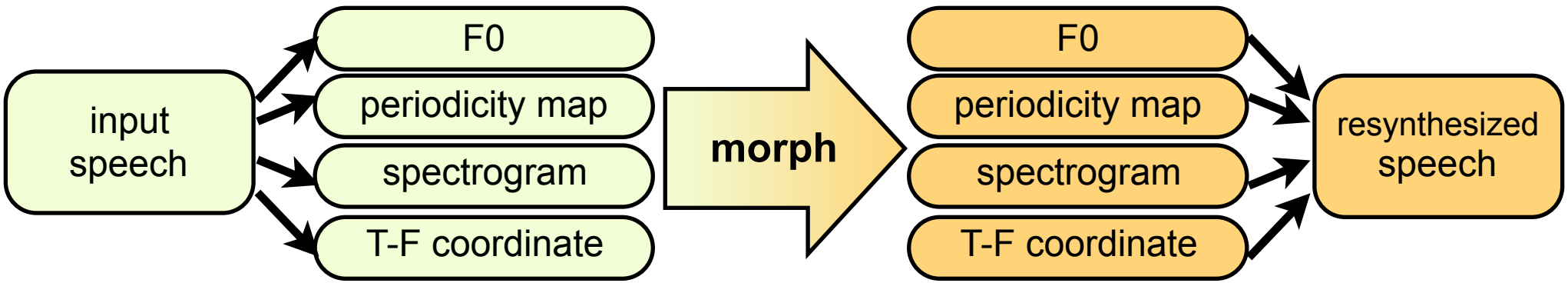
Spectrum to spectrum envelope

- From spectrums to spectrum envelopes
  - log-amplitude spectrum -> smoothing -> spectrum envelope
- Humans' insensitivity to pitch differences when perceiving phonemes.
  - /a/ with high tone and /a/ with low tone are perceived to be of the same class.
  - Separation of pitch (fundamental frequency) can be done by spectrum smoothing.



Advanced technology for analysis

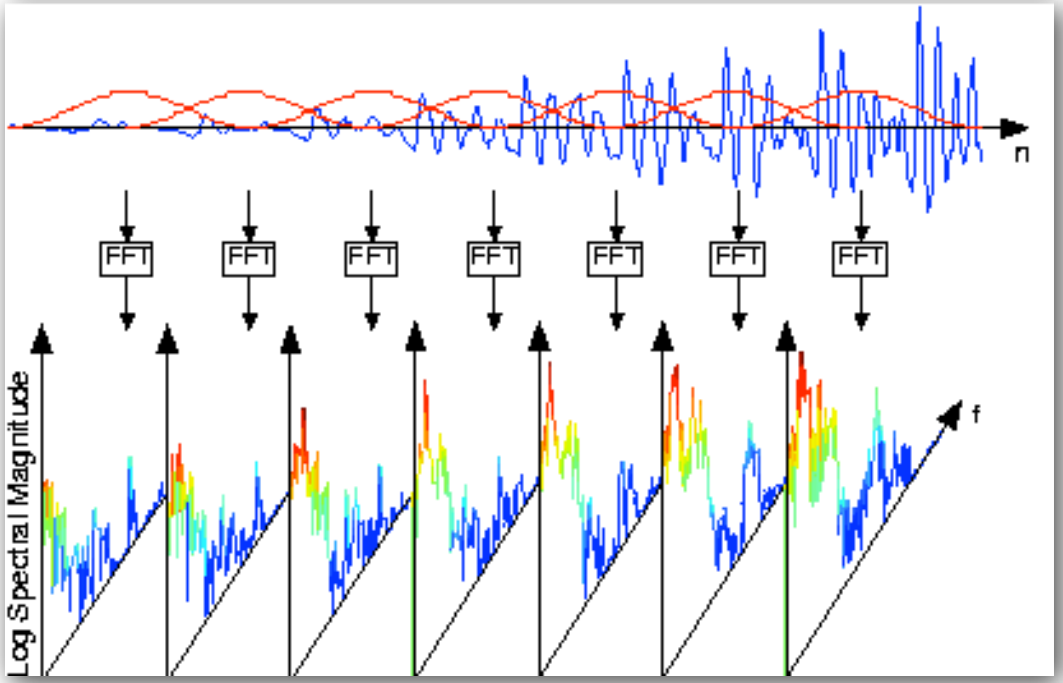
- STRAIGHT [Kawahara'06]
  - High-quality analysis-resynthesis tool
    - Decomposition of speech into
      - Fundamental frequency, spectrographic representations of power, and that of periodicity
    - High-quality speech morphing tool

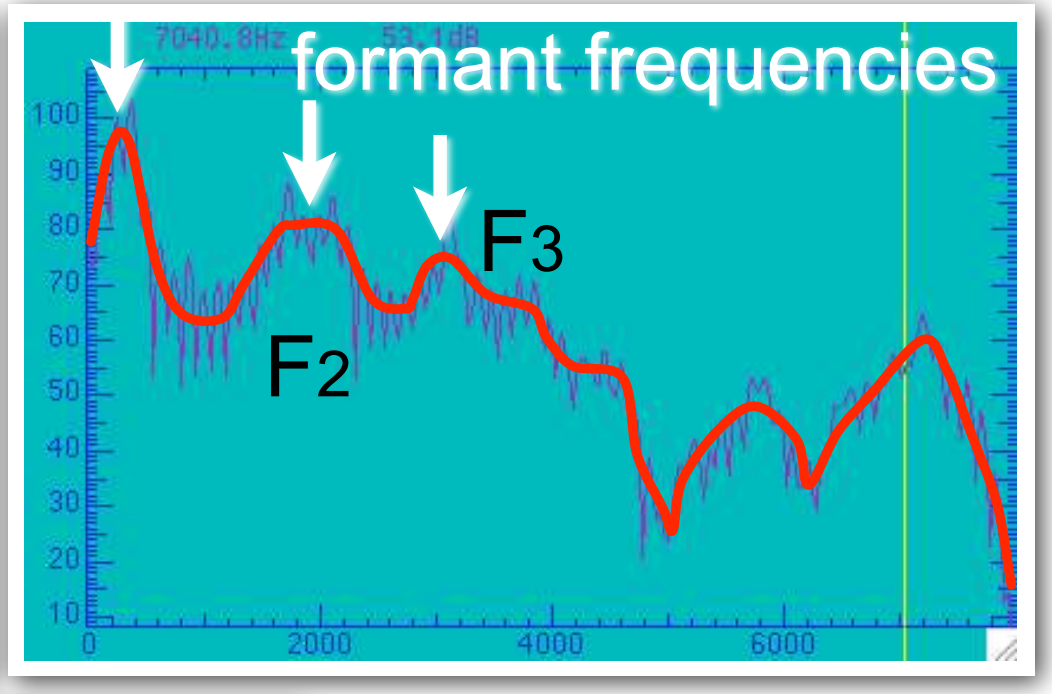


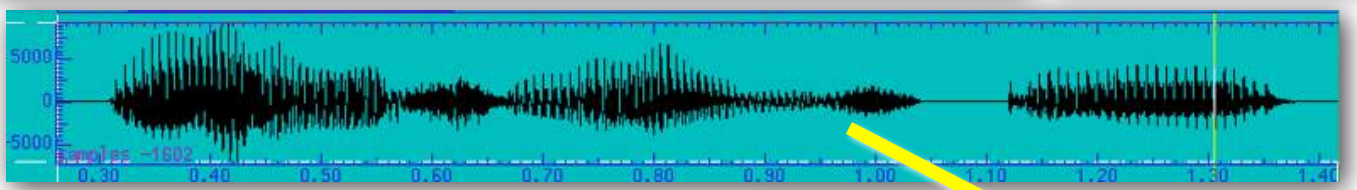
  - Spectrographic representation of power
    - F0 adaptive complementary set of windows and spline based optimal smoothing
  - Instantaneous frequency based F0 extraction
    - With correlation-based F0 extraction integrated
  - Spectrographic representation of periodicity
    - Harmonic analysis based method

Acoustic phonetics

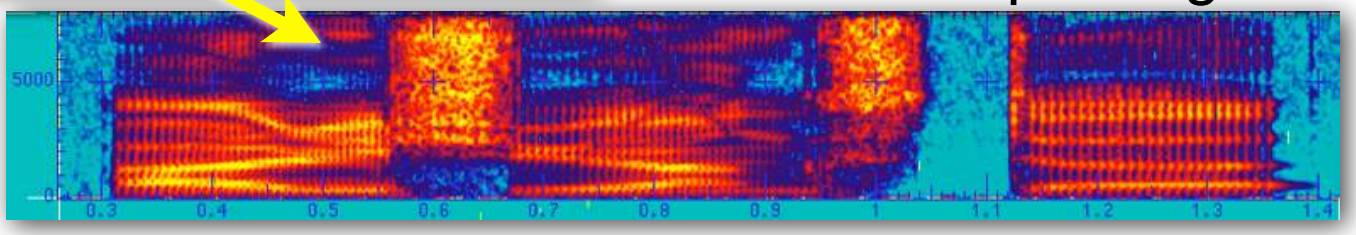
- From waveforms to spectrums
  - Windowing + FFT + log-amplitude





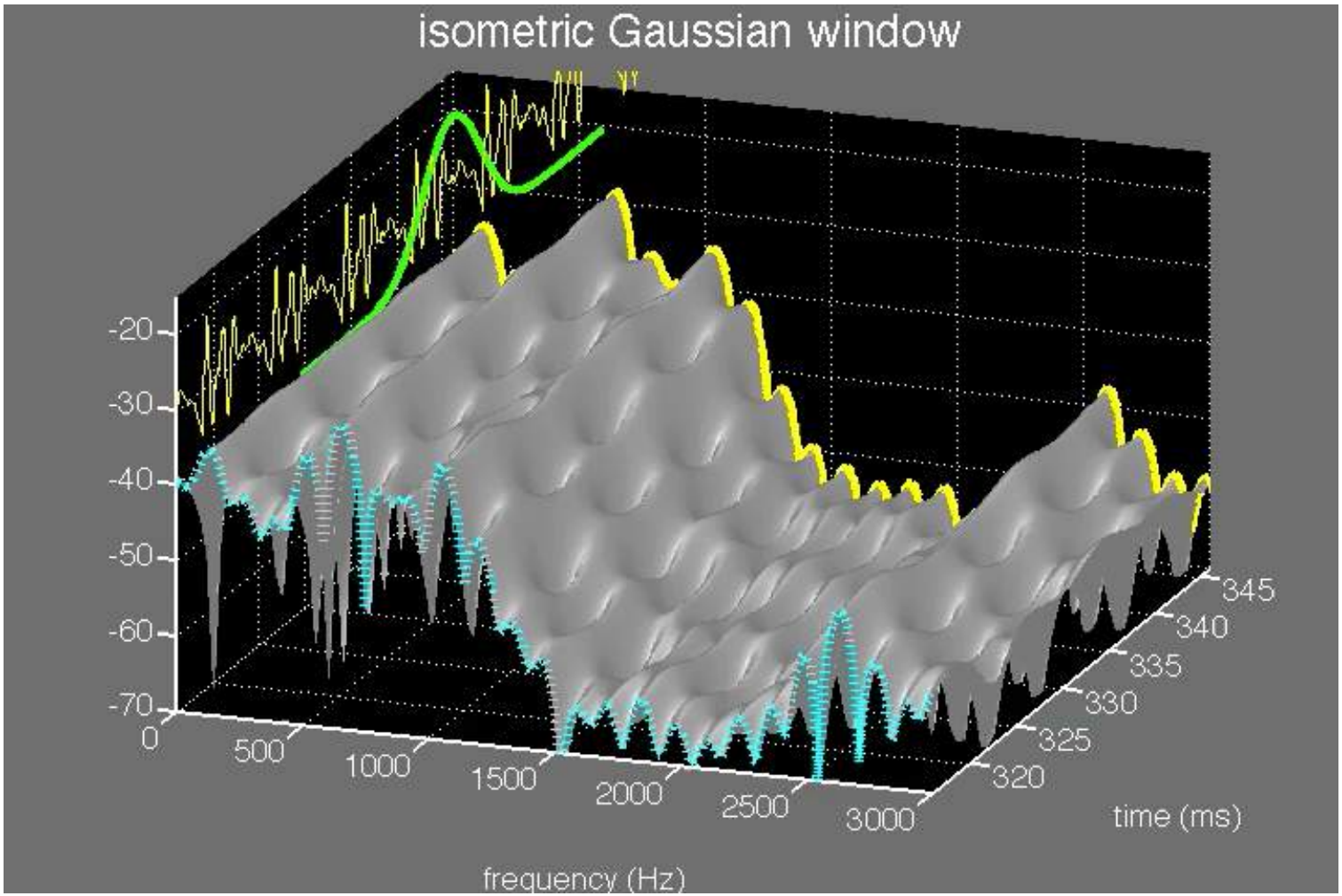


spectrogram



Advanced technology for analysis

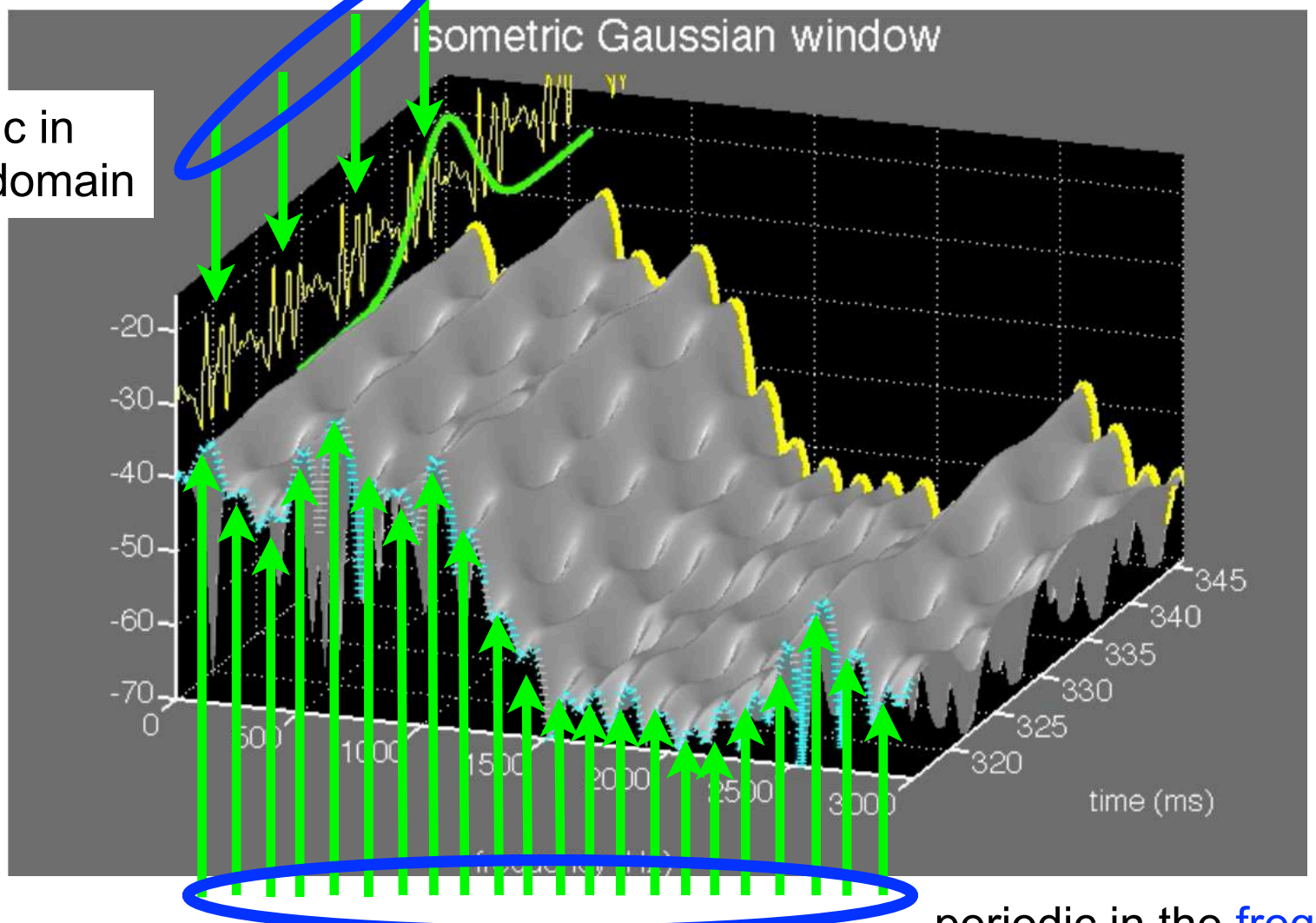
- Short Time Fourier Transform (STFT)-based spectrogram



Advanced technology for analysis

- Short Time Fourier Transform (STFT)-based spectrogram

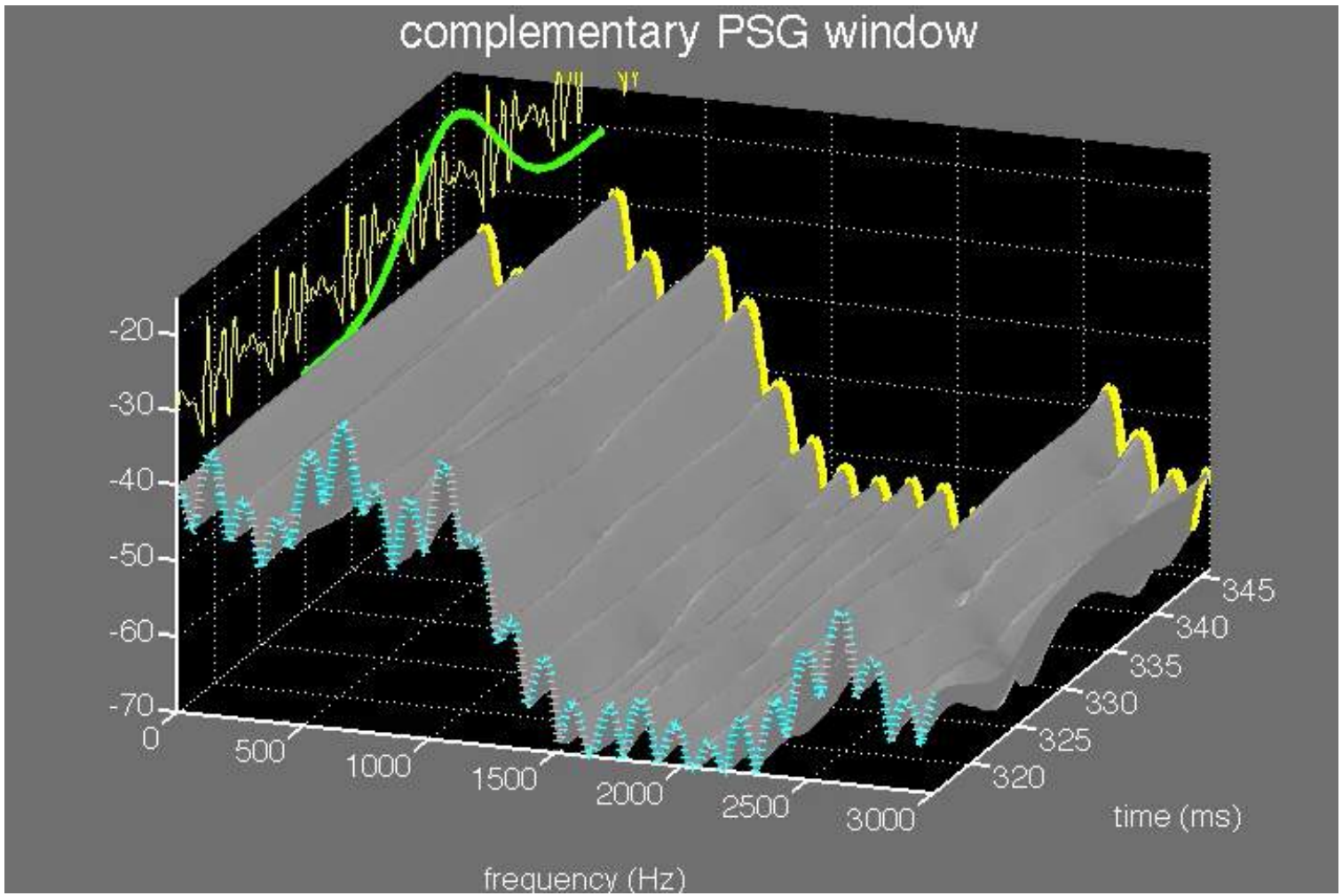
periodic in the time domain



periodic in the freq. domain

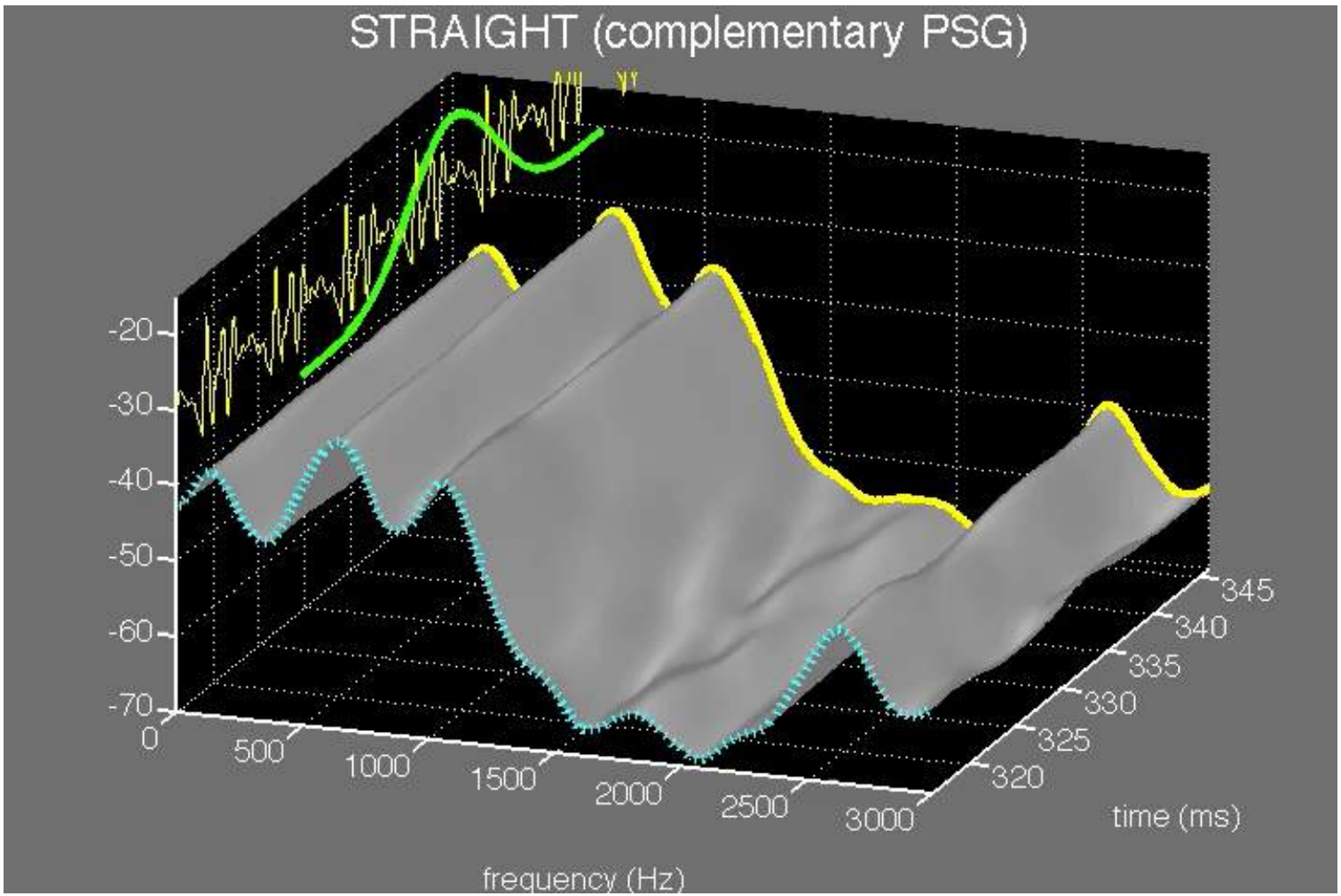
Advanced technology for analysis

- Complementary pitch-synchronous Gaussian window removes the repetitive structure in the time domain.

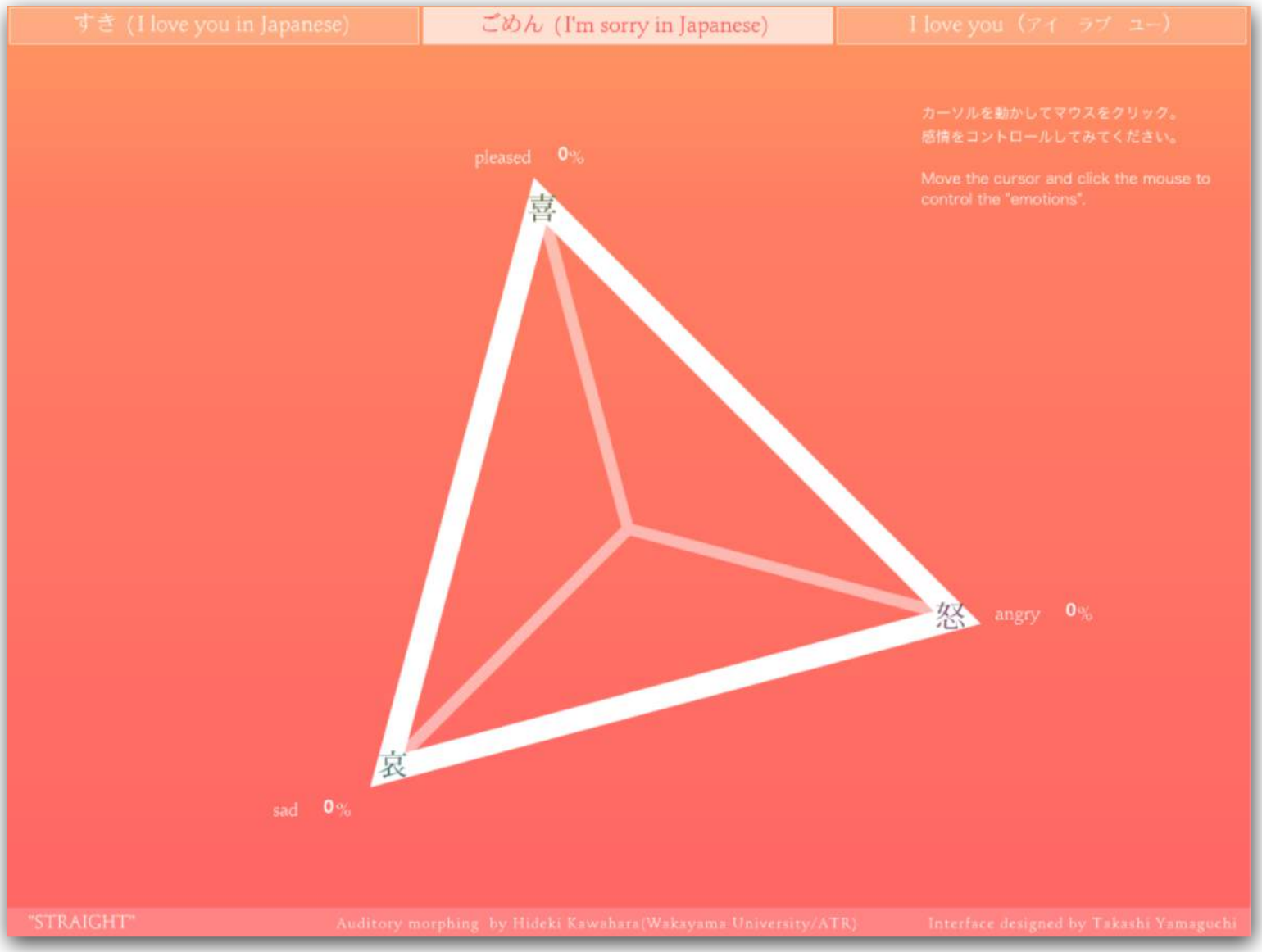


Advanced technology for analysis

- Spline-based optimum smoothing reconstructs the underlying smooth time-frequency representation.

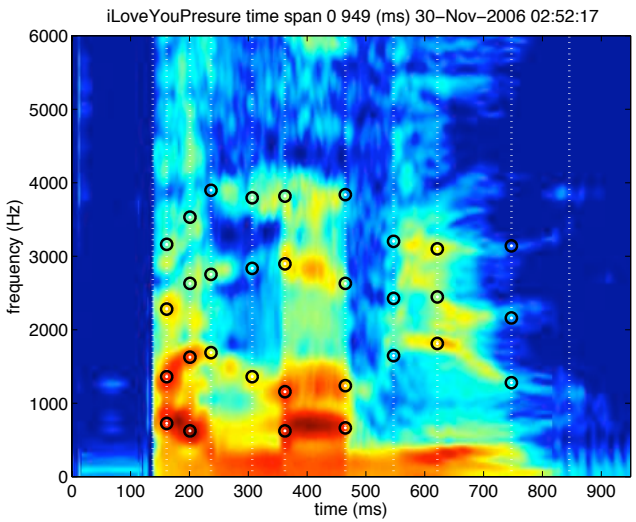


Examples of speech morphing



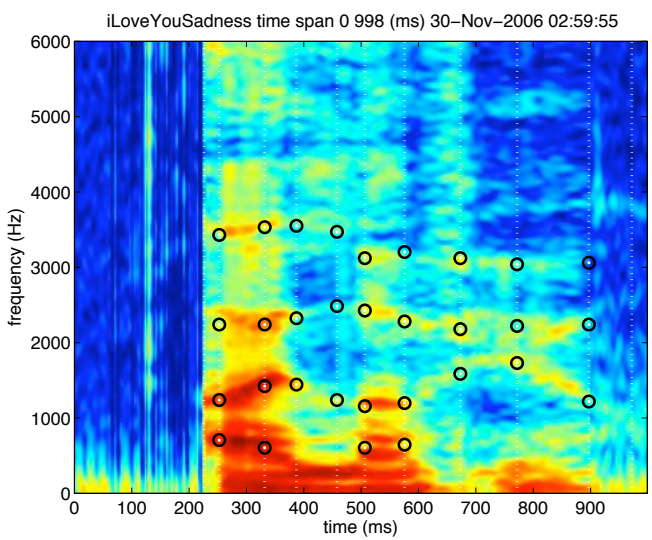
Examples of speech morphing

- Morphing with some anchor points

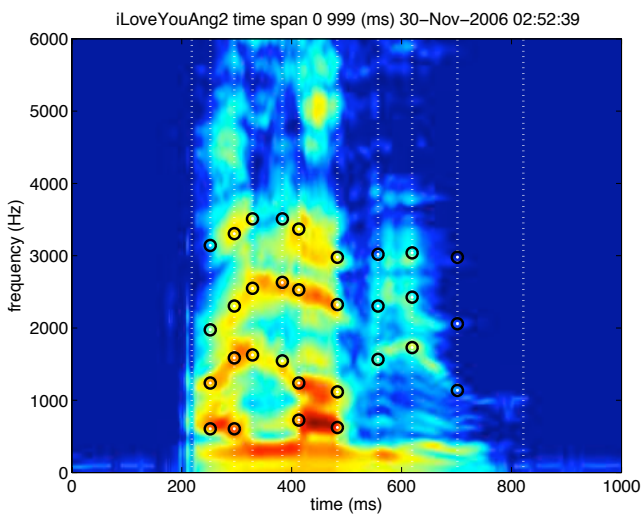


Pleasure

Sadness

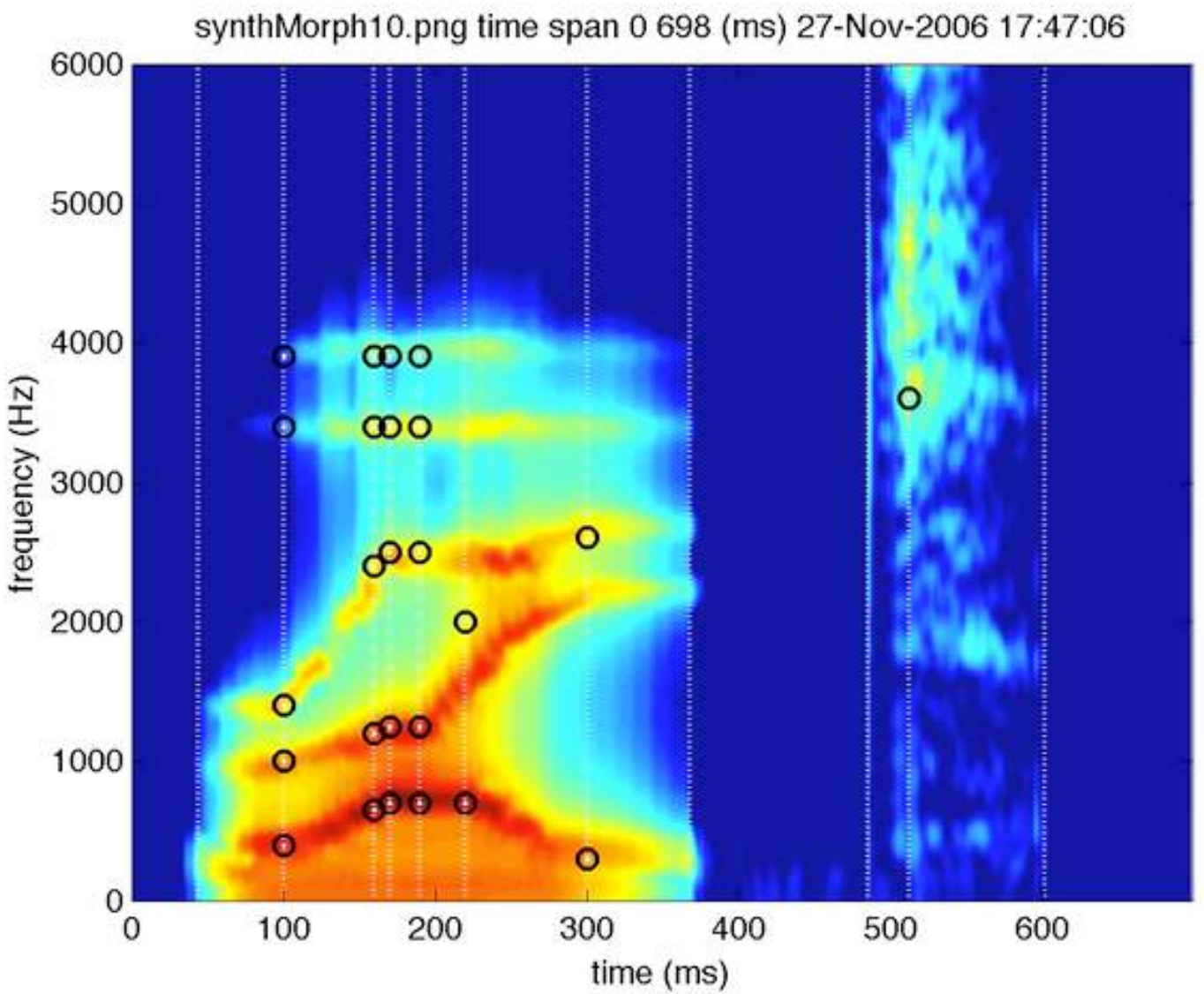


Anger



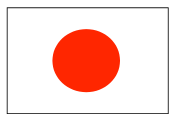
Examples of speech morphing

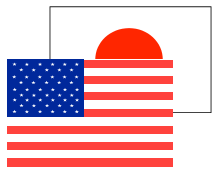
- R to L morphing bet. r/l-ight generated by Klatt synthesizer [Kubo+'98]



Examples of speech morphing

- Morphing of native utterance and its accented version [Kato+'11]
  - Use of a pair of word utterances spoken by a bilingual speaker
    - Normal Tokyo Japanese
    - Heavily American accented Japanese





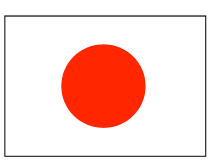
fundamental frequency (F0) → 3.

phonetic duration (dur) → 4.

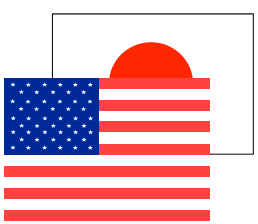
spectral envelope & aperiodicity (sp_ap) → 5.

F0 & dur (F0_dur) → 6.

all the parameters (all) → 7. = 2.



1.



2.

0 0.25 0.5 0.75 1

morphing rate

Vocal tract shape and spectrum envelope

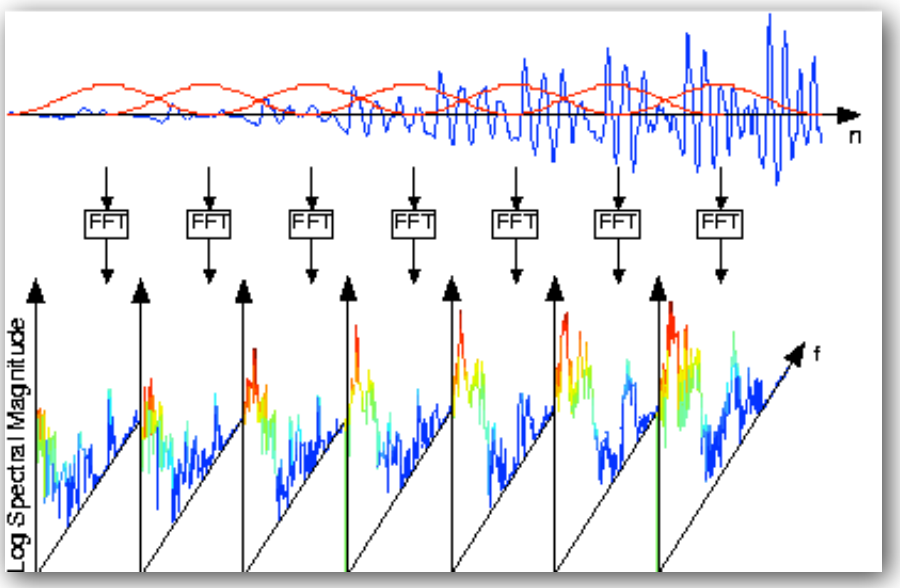
- Linear Predictive Coding (LPC)
  - Speech signal at time t, s_t, is predicted as weighted addition of some old signals.

$$s_t \leftarrow -\sum_{k=1}^{p} \alpha_k s_{t-k}$$

$$s_t + \sum_{k=1}^{p} \alpha_k s_{t-k} = \sum_{k=0}^{p} \alpha_k s_{t-k} = \varepsilon_t \quad (\alpha_0 = 1.0)$$

$$S(z) + \alpha_1 S(z) z^{-1} + \alpha_2 S(z) z^{-2} + \cdots + \alpha_p S(z) z^{-p} = E(z)$$

$$S(z) = \frac{1}{1 + \alpha_1 z^{-1} + \alpha_2 z^{-2} + \cdots + \alpha_p z^{-p}} E(z) = A(z) E(z)$$

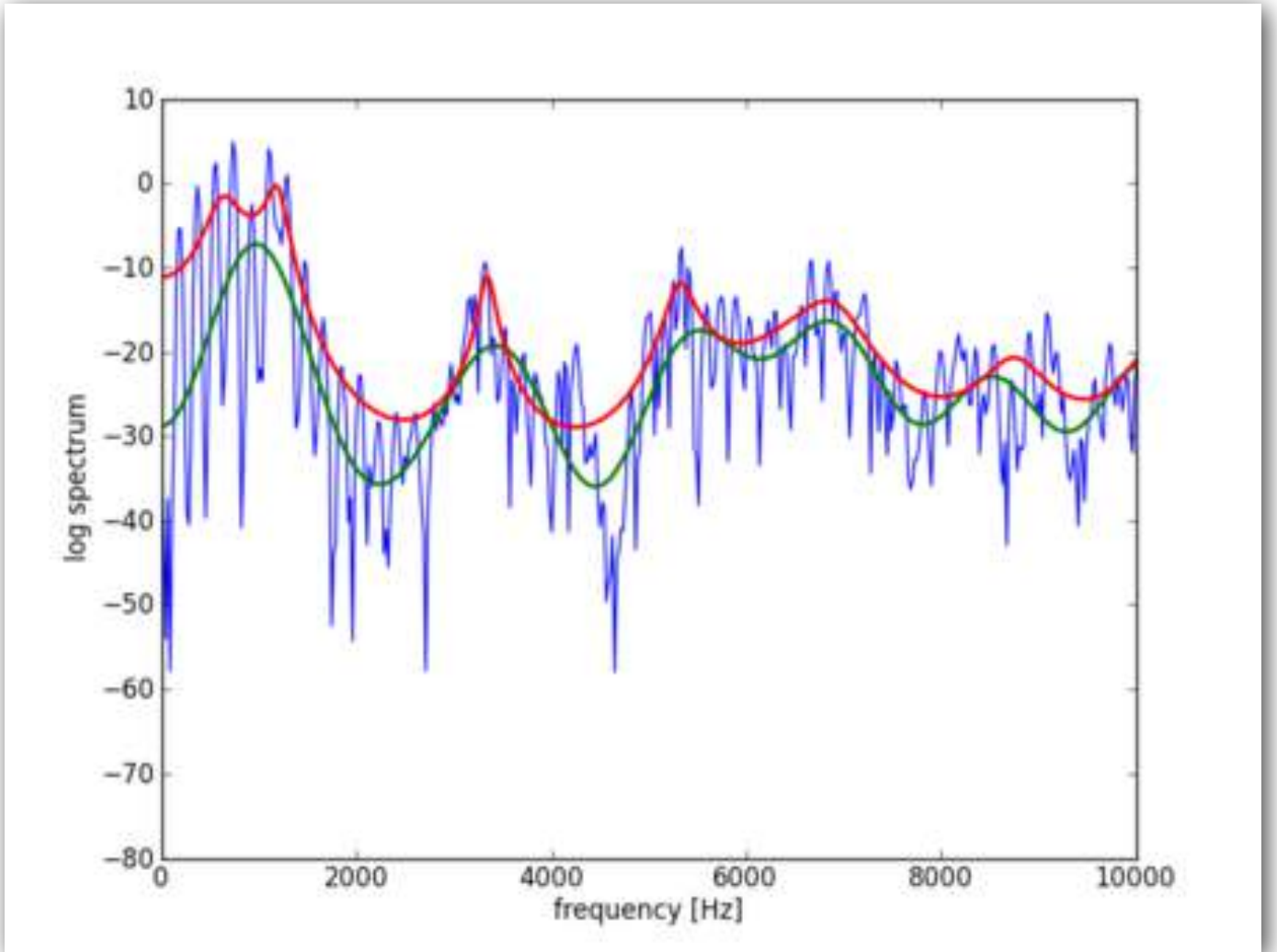


$\{\alpha_k\}$ are estimated for a frame in such a way that error term for that frame, ε_t, should be minimized.

If error term is assumed to be white noise, then, the spectrum envelope shape is determined by A(z).

Spectrum envelopes by CEP and LPC

- Cepstrum-based envelope is just a smoothed spectrum.
- Spectral peaks are emphasized in LPC-based envelope.



LPC to vocal tract area function

- $\{\alpha_k\}$ to the area function of the vocal tube.
  - LPC coefficients are transformed into PARCOR (PARtial auto-CORrelation) coefficients.
  - PARCOR coeff. are transformed to reflection coefficients between two consecutive short tubes.
  - Finally PARCOR coefficients are related to the cross-sectional area of each short tube.

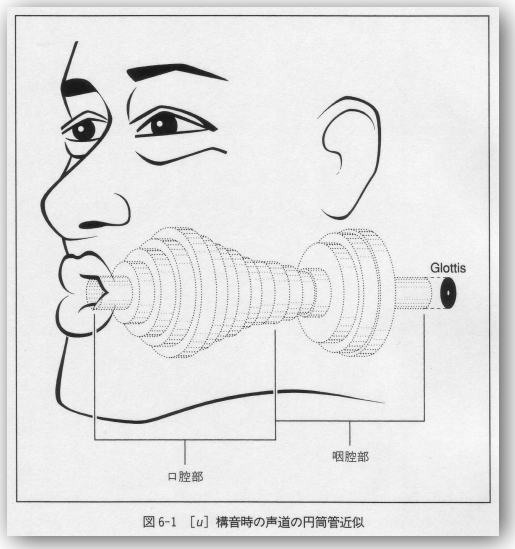
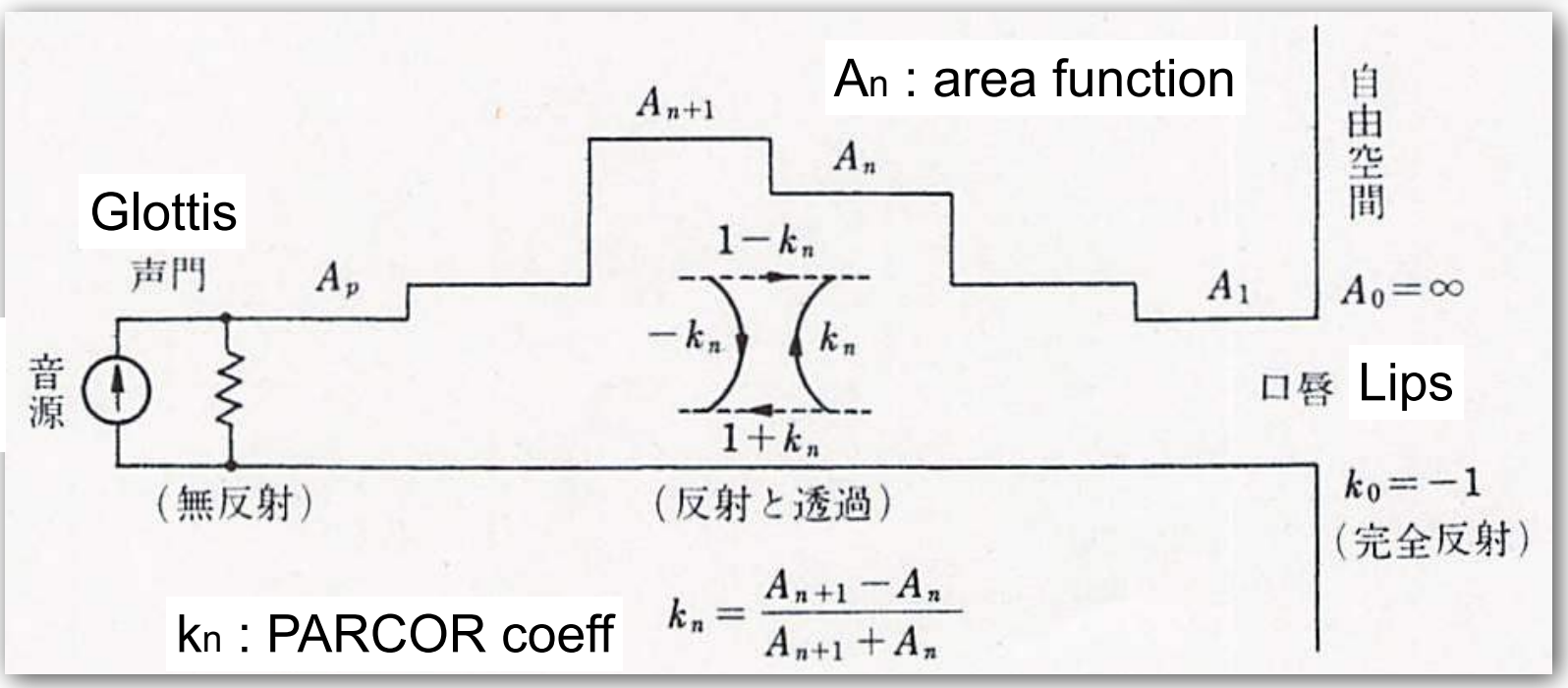


図 6-1 ［u］構音時の声道の円筒管近似



Today's menu

- More on details of acoustic phonetics (continued)
  - Characteristics of human hearing
  - Fundamental frequency and pitch again
  - Fourier analysis of speech signals
  - Simple hearing tests

- Technology for acoustic analysis of speech
  - Source-filter model of speech production $S(\omega) = G(\omega)H(\omega)R(\omega)$
  - Cepstrum method to separate source and filter
  - Advanced analysis tool of STRAIGHT
  - Some morphing examples
  - LPC, PARCOR, and the shape of a vocal tube

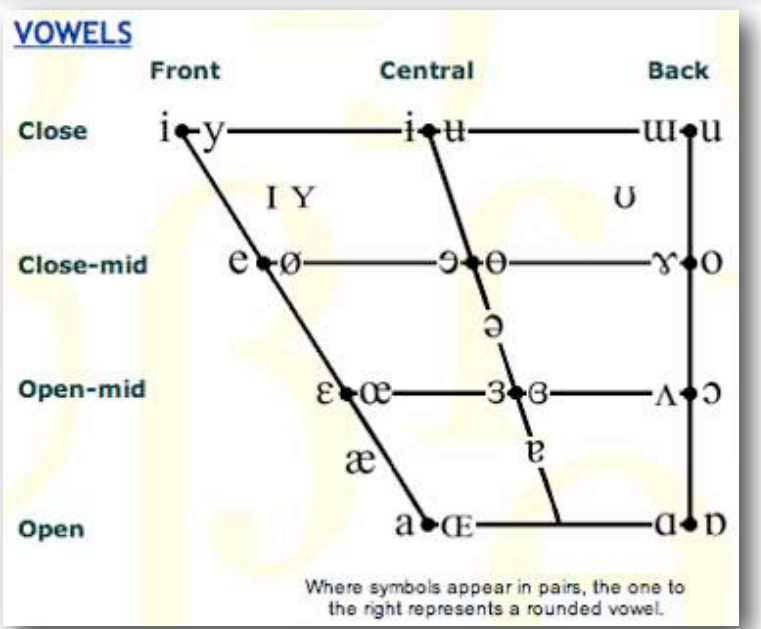
- Spectrums/waveforms of various language sounds
  - Vowels, semivowels, liquids, nasals, voiced fricatives, unvoiced fricatives, glottals,
  - voiced plosives, unvoiced plosives, voiced affricatives, and unvoiced affricatives
  - Speech recognition as spectrum reading
- Summary

Various sounds in languages

CONSONANTS (PULMONIC)

	Bilabial	Labiodental	Dental	Alveolar	Postalveolar	Retroflex	Palatal	Velar	Uvular	Pharyngeal	Glottal
Plosive	p b			t d		ʈ ɖ	c ɟ	k g	q G		ʔ
Nasal	m	ɱ		n		ɳ	ɲ	ŋ	N		
Trill	ʙ			r					ʀ		
Tap or Flap				ɾ		ɽ					
Fricative	ɸ β	f v	θ ð	s z	ʃ ʒ	ʂ ʐ	ç ʝ	x ɣ	χ ʁ	ħ ʕ	h ɦ
Lateral fricative				ɬ ɮ							
Approximant		ʋ		ɹ		ɻ	j	ɰ			
Lateral approximant				l		ɭ	ʎ	ʟ			

Where symbols appear in pairs, the one to the right represents a voiced consonant. Shaded areas denote articulations judged impossible.



Vowels

- Characteristics of vowels
  - Front vowels of /i/ and /e/: resonance at higher frequency bands
  - Middle vowels of /a/: energy distribution over a wide frequency range
  - Back vowels of of /u/ and /o/: lower bands are dominant in energy distribution
  - Unvoiced vowels

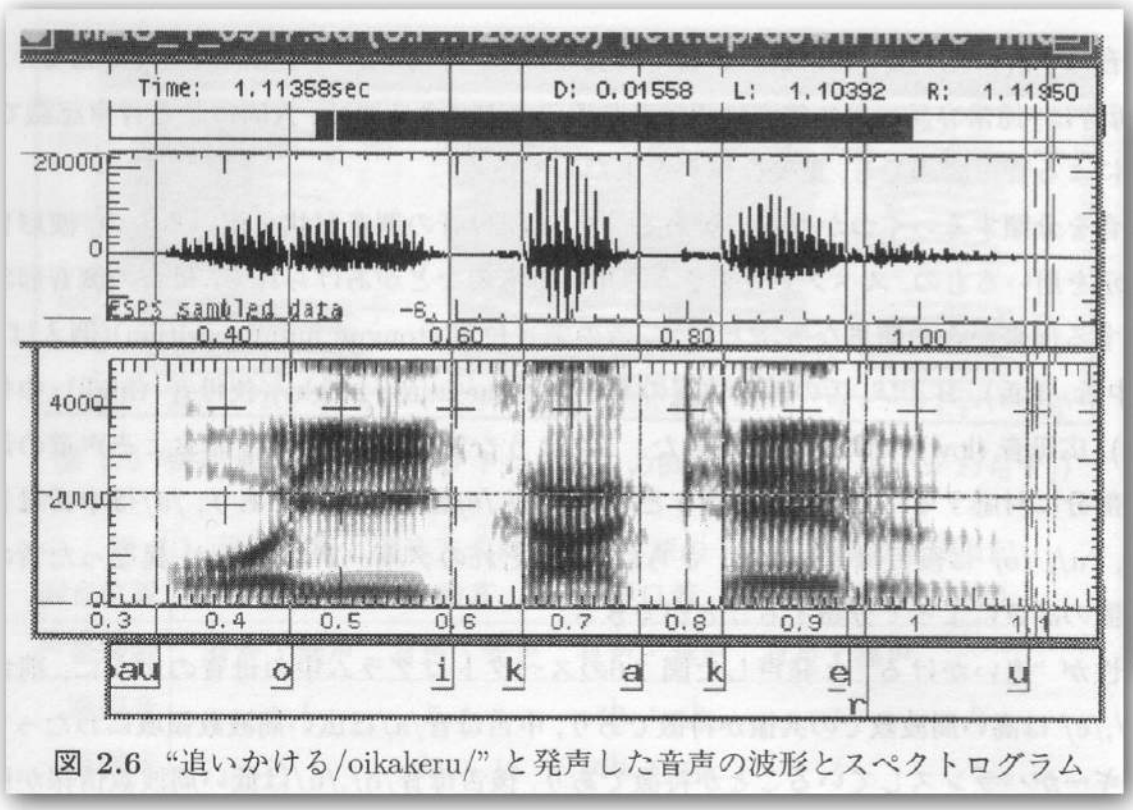


図 2.6 “追いかける/oikakeru/” と発声した音声の波形とスペクトログラム

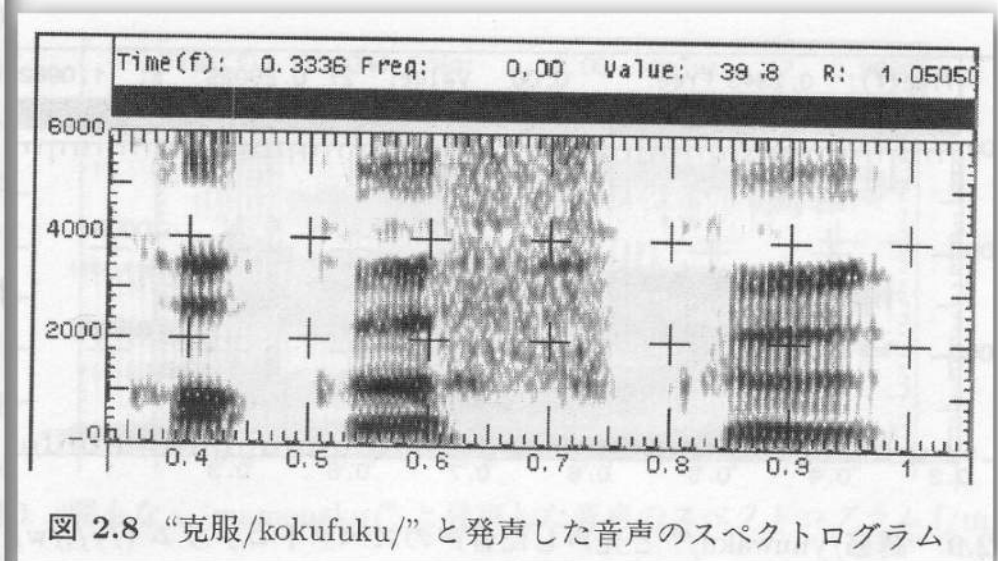


図 2.8 “克服/kokufuku/” と発声した音声のスペクトログラム

Semivowels and liquids

- Characteristics of semivowels and liquids
  - /w/, /y/, and /r/: characterized by their transitional parts from/to neighboring phones.
  - Large dependency on phonemic context.

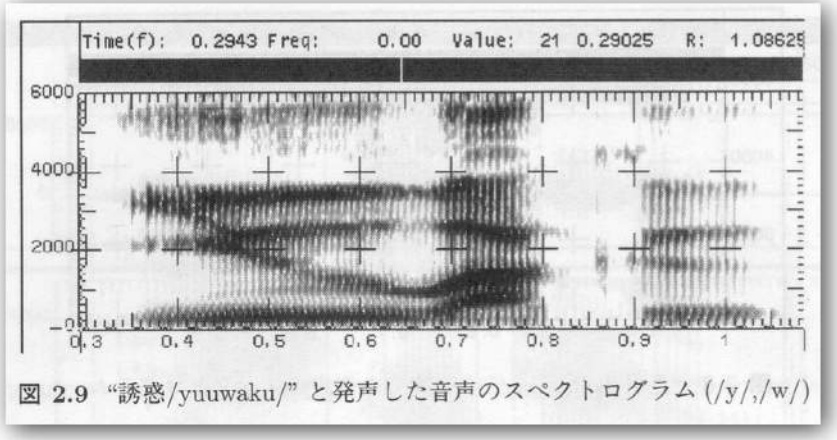


図 2.9 “誘惑/yuuwaku/” と発声した音声のスペクトログラム (/y/,/w/)

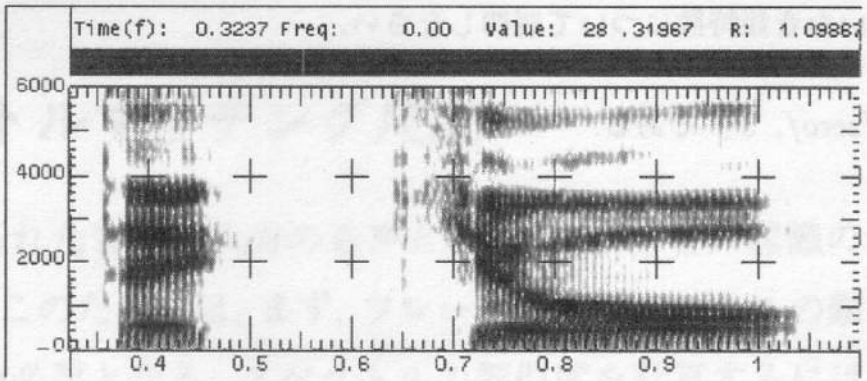


図 2.17 “鉄橋/teQkyo-/” と発声した音声のスペクトログラム (/t/,/Q/,/ky/)

Nasals

- Characteristics of nasals
  - /m/, /n/, /ng/, /N/: a pathway to the nasal cavity shows its own acoustic features.
  - Closed vocal cavity and open nasal cavity cause antiresonance.
  - Transitional parts from/to neighboring vowels are useful in identifying nasal sounds.

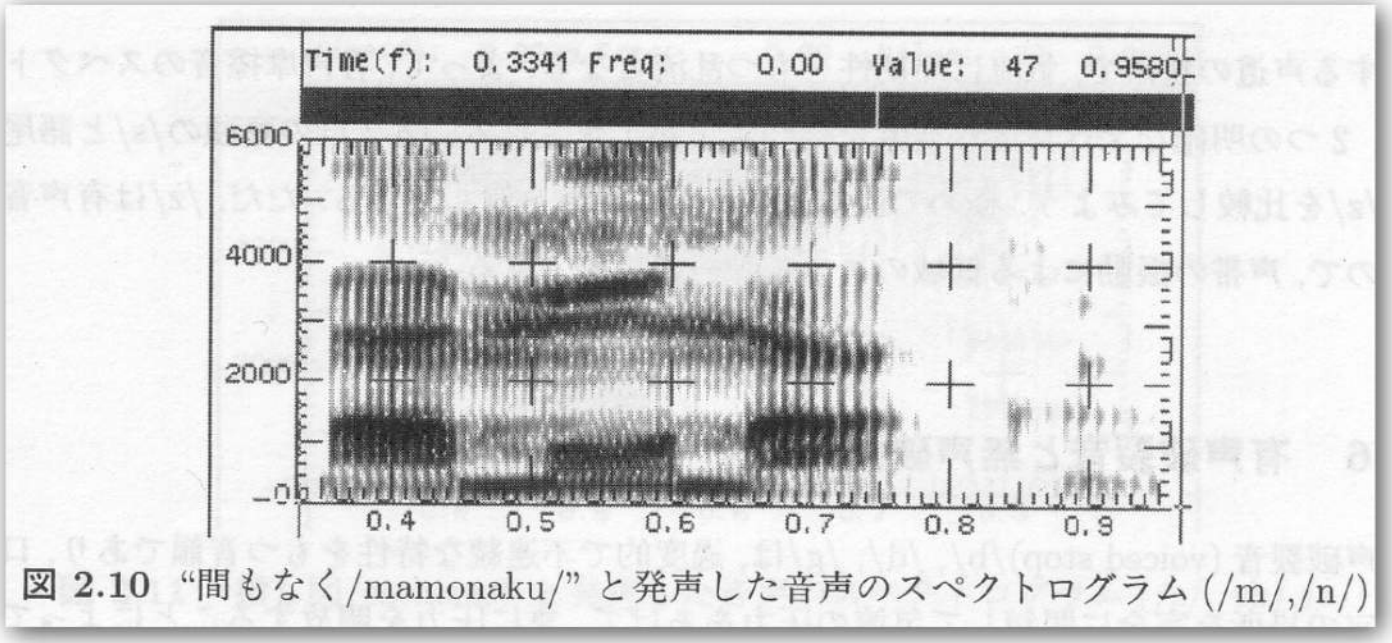


図 2.10 “間もなく/mamonaku/” と発声した音声のスペクトログラム (/m/,/n/)

Unvoiced fricatives and glottals

- Characteristics of unvoiced fricatives and glottals
  - /f/, /s/, /sh/: energy distribution at higher frequency bands
  - A vocal cavity from the (almost) closing point to the lung causes antiresonance.

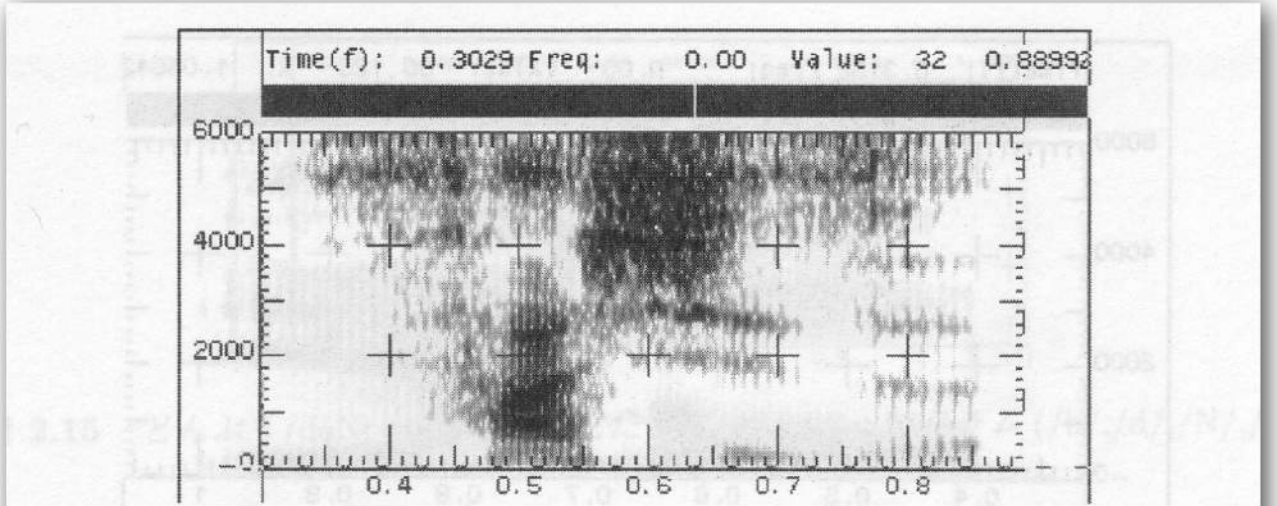


図 2.11 “指し図/sashizu/” と発声した音声のスペクトログラム (/s/,/sh/,/z/)

  - /h/: fricative at glottis
    - The shape of the vocal cavity is the same as that of the succeeding vowel.
    - No antiresonance

Voiced fricatives

- Characteristics of voiced fricatives
  - /v/, /z/, /zh/: source sounds are generated at two positions, glottal sources and fricative sources
  - Energy distribution is found at a very low frequency band due to the glottal source.

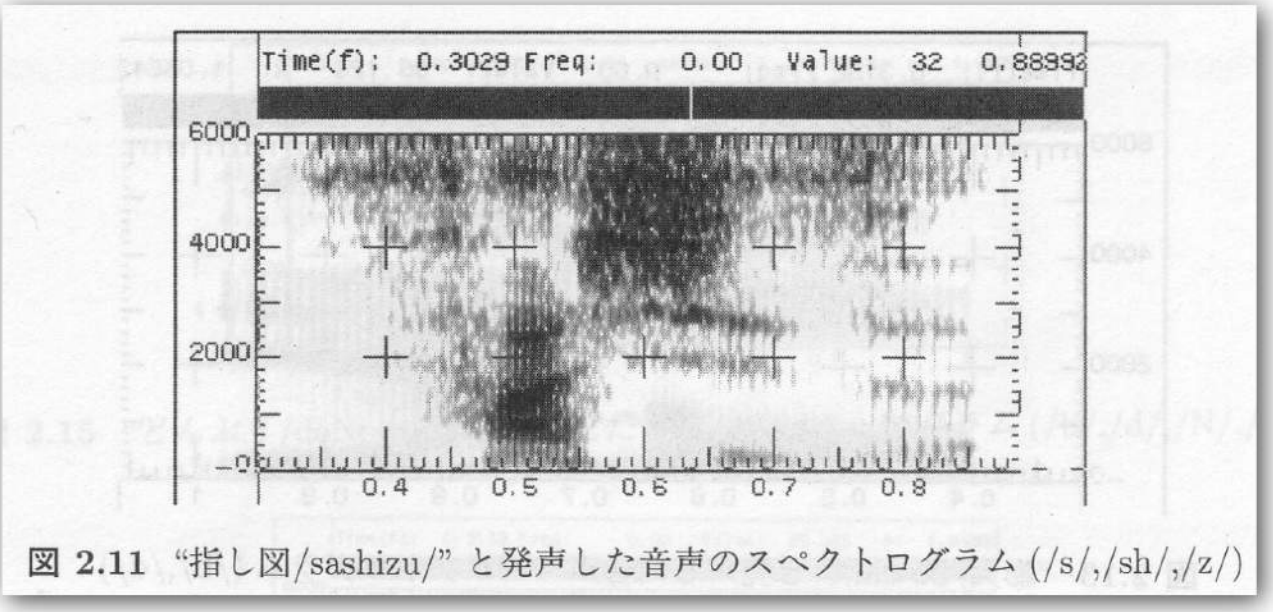


図 2.11 “指し図/sashizu/” と発声した音声のスペクトログラム (/s/,/sh/,/z/)

Voiced plosives and unvoiced plosives

- Characteristics of voiced plosives and unvoiced plosives
  - /b/, /d/, /g/ /p/, /t/, /k/
  - Complete closure in the vocal tract at a time and abrupt release of air flow
  - Buzz-bar: closed vocal tract + vocal fold vibration --> radiation from the skin
  - Transitional parts from/to neighboring vowels are useful in identifying nasal sounds.

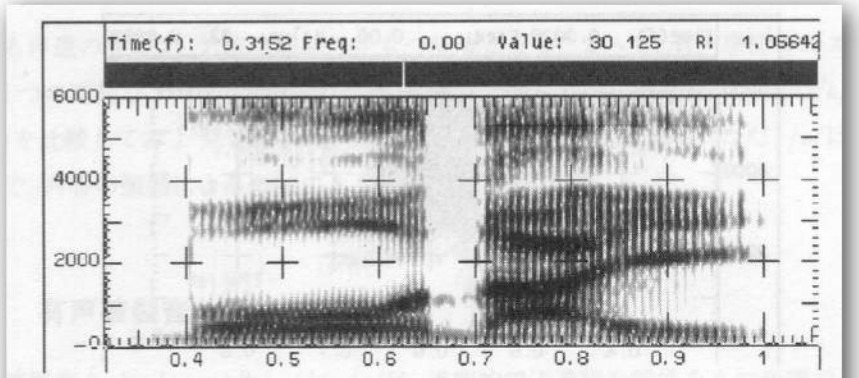


図 2.13 “膨大/bo-dai/” と発声した音声のスペクトログラム (/b/,/d/)

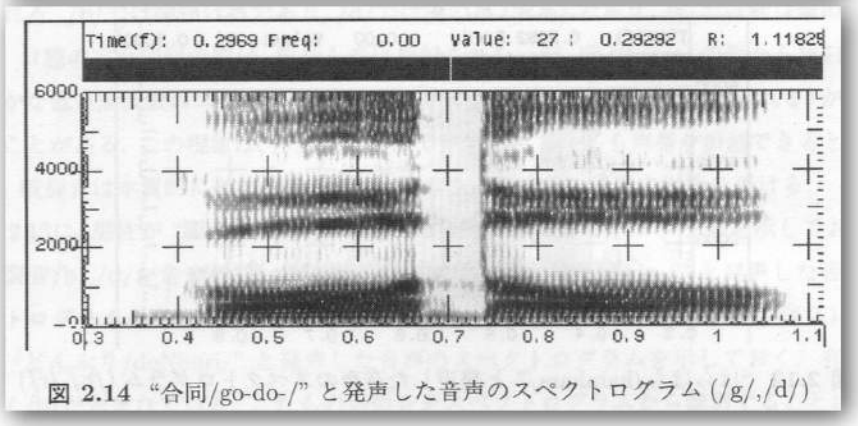


図 2.14 “合同/go-do-/” と発声した音声のスペクトログラム (/g/,/d/)

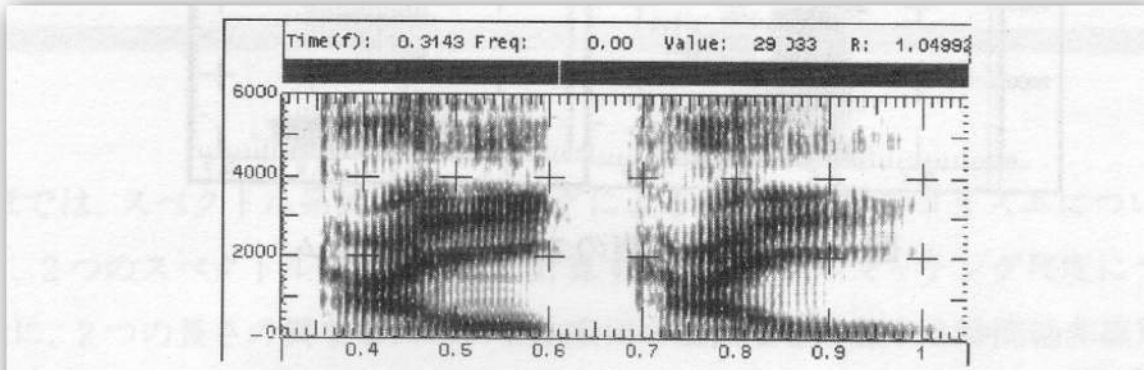


図 2.16 “大会/taikai/” と発声した音声のスペクトログラム (/t/,/k/)

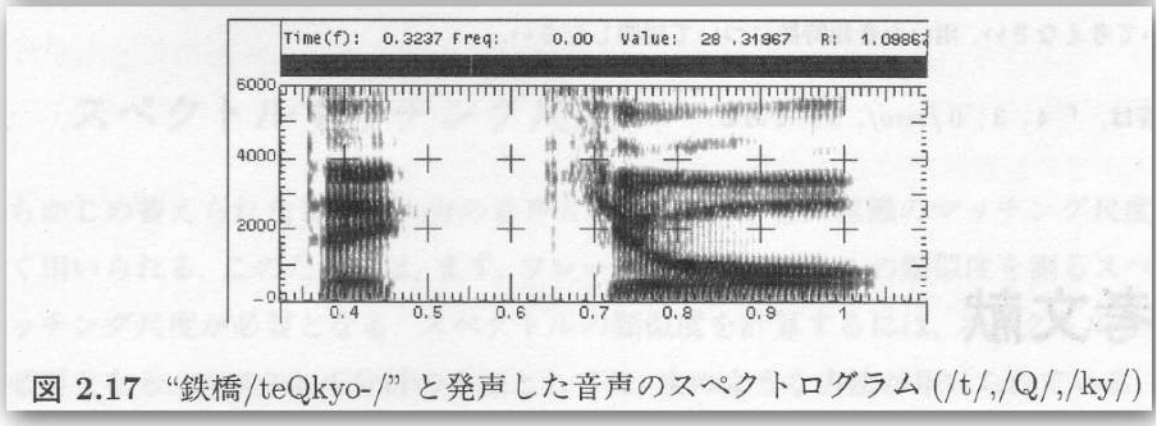


図 2.17 “鉄橋/teQkyo-/” と発声した音声のスペクトログラム (/t/,/Q/,/ky/)

Voiced affricates and unvoiced affricates

- Characteristics of voiced affricates and unvoiced affricates
  - Affricate = plosive + fricative
  - /dz/, /dh/,　/ts/, /ch/

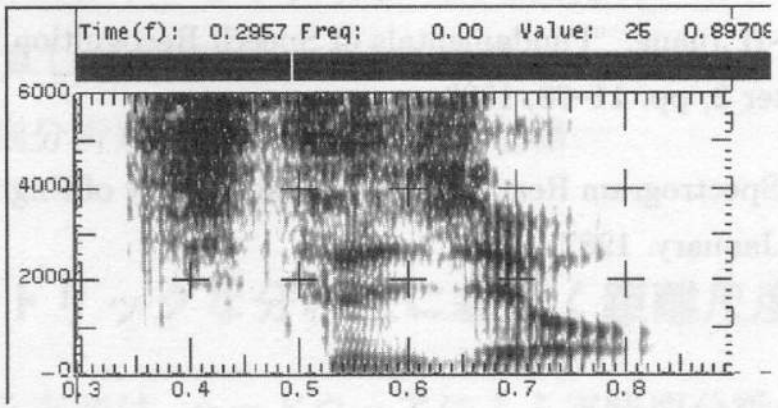


図 2.18 “秩序/chitsujo/” と発声した音声のスペクトログラム (/ch/,/ts/,/zh/)

Spectrum reading

- What are these?
  - Hint : they are numbers.

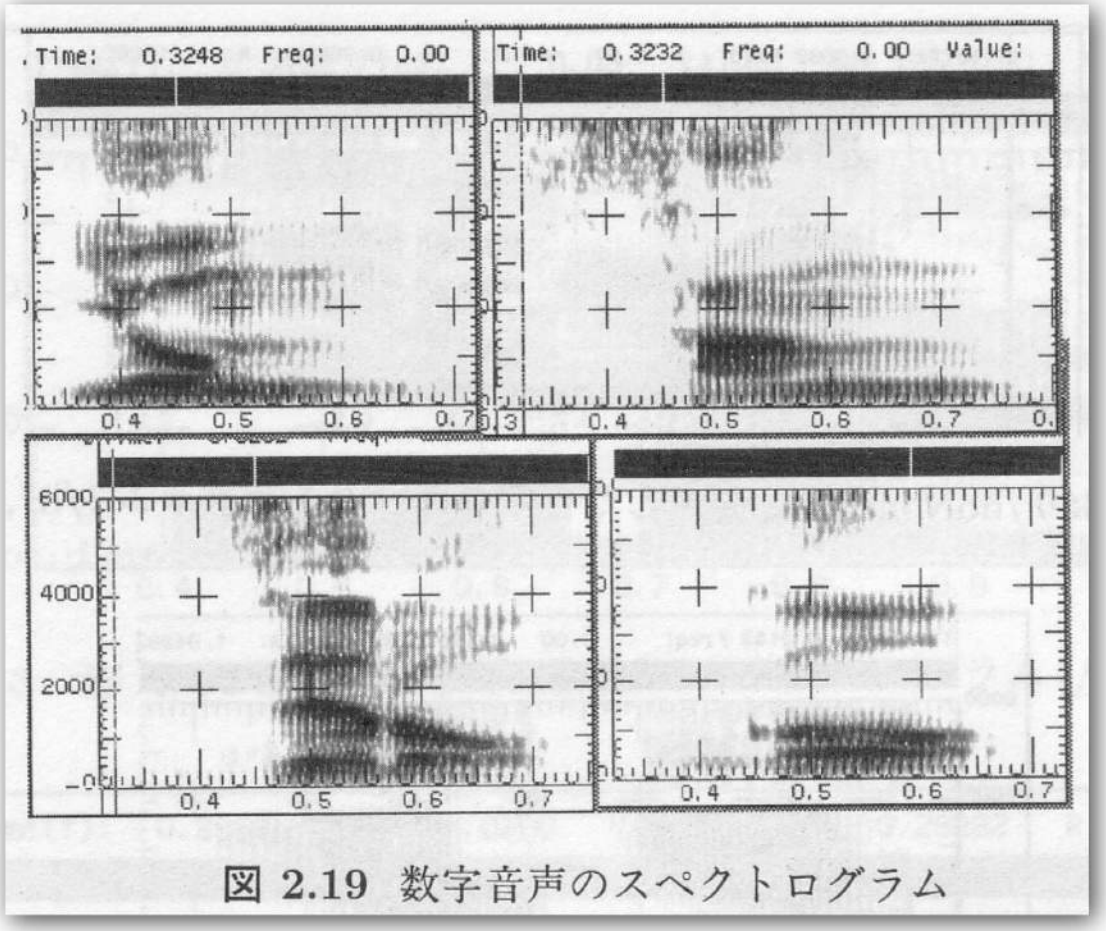


図 2.19 数字音声のスペクトログラム

- This is the task that is done by a speech recognizer.

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