speech

CSC401/2511 – Natural Language Computing – Spring 2022
Lecture 8
University of Toronto

This lecture

- Acoustics.
- Speech production.
- Speech perception.

- Some images from Gray's Anatomy, Jim Glass' course 6.345 (MIT), the Jurafsky & Martin textbook, Encyclopedia Britannica, the Rolling Stones, the Pink Floyds.

acoustics

What is sound?

- **Sound** is a time-variant pressure wave created by a vibration.
  - Air particles **hit** each other, setting others in motion.
    - High pressure ≡ **compressions** in the air (C).
    - Low pressure ≡ **rarefactions** within the air (R).

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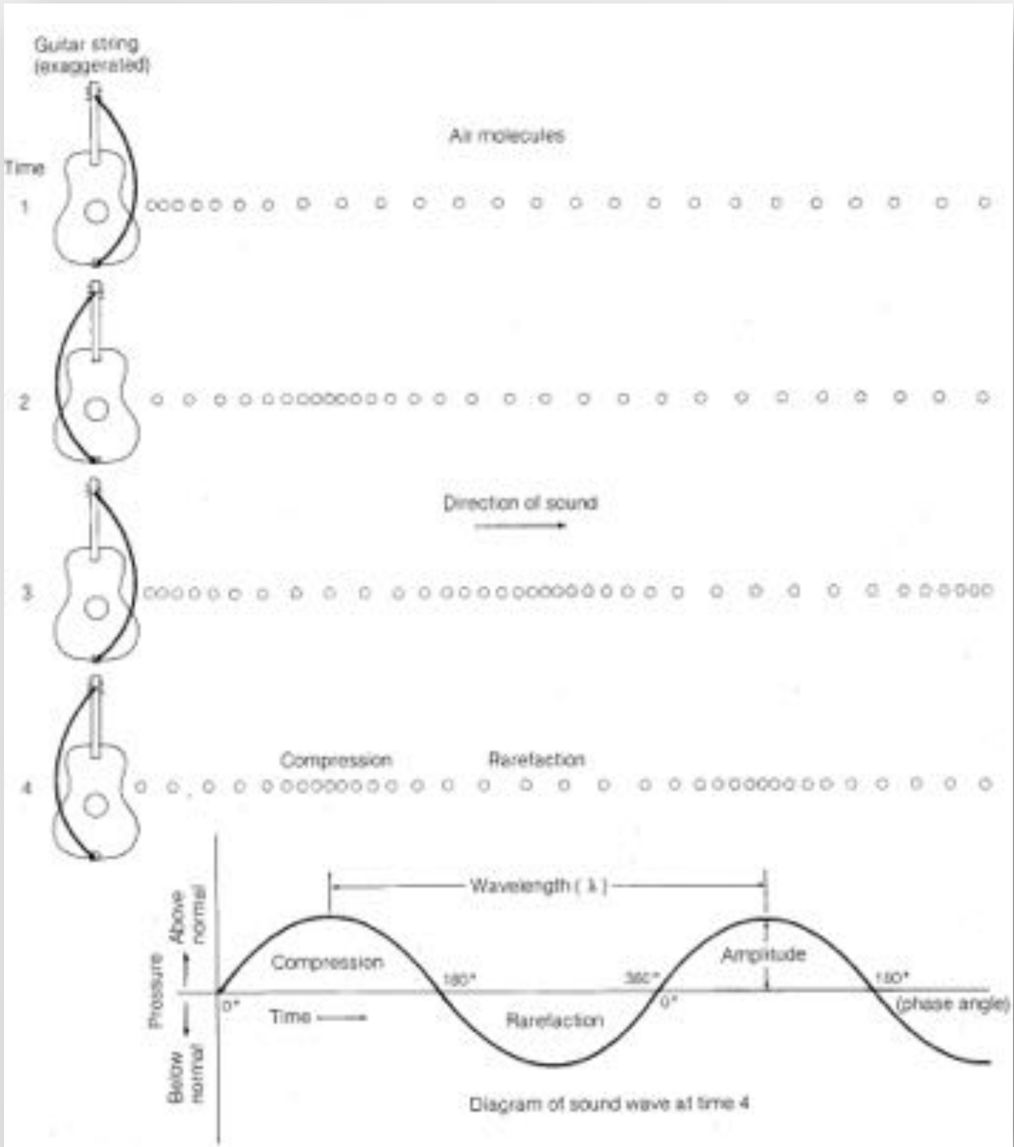
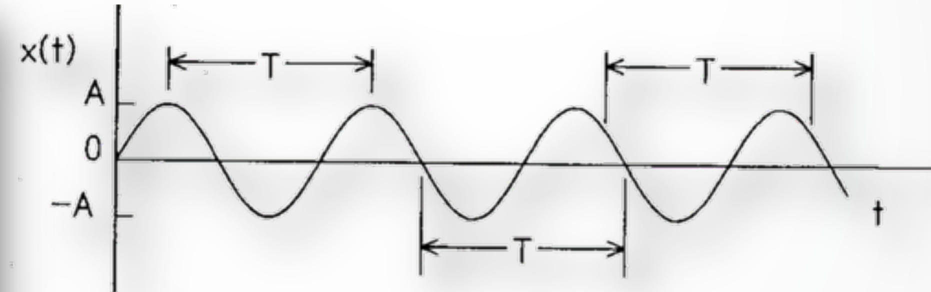
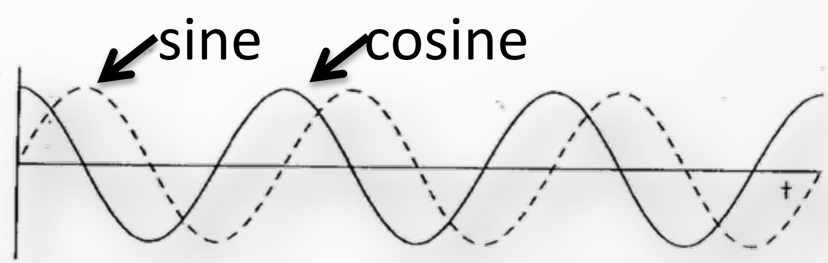
What is sound?





Frequency $F = 1/T$



phase ϕ is displacement of a signal in time. E.g., with $\phi = \pi/2$,

$$\sin(x + \phi) = \cos(x)$$

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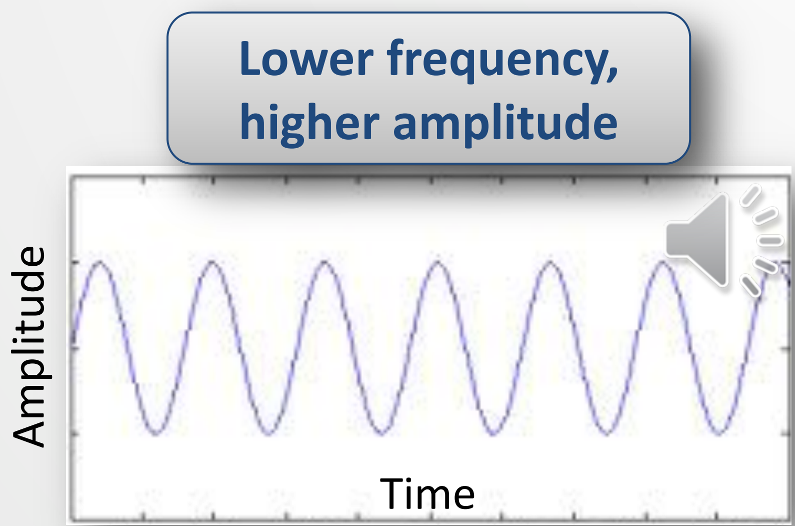
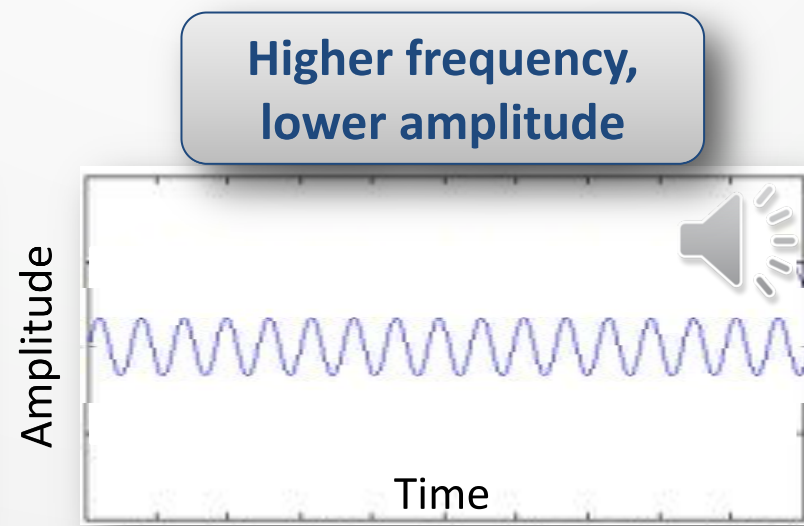
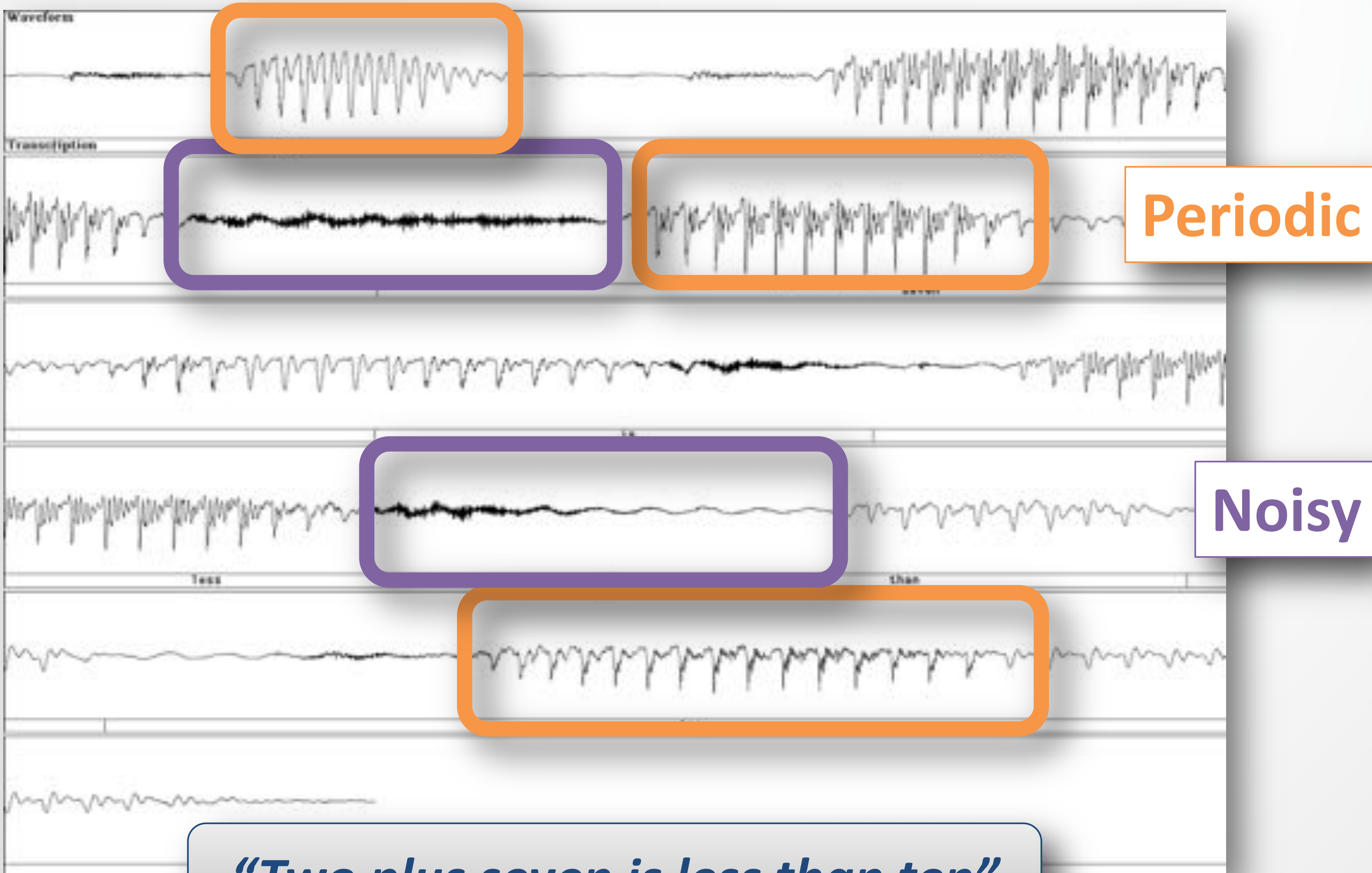
What is sound?

- A single **tone** is a sinusoidal function of pressure and time.
  - **Amplitude**: *n.* The degree of the displacement in the air. This is similar to 'loudness'. Often measured in **Decibels (dB)**.
  - **Frequency**: *n*. The number of cycles within a unit of time. e.g., **1 Hertz (Hz) = 1 oscillation/second**





Speech waveforms



"Two plus seven is less than ten"

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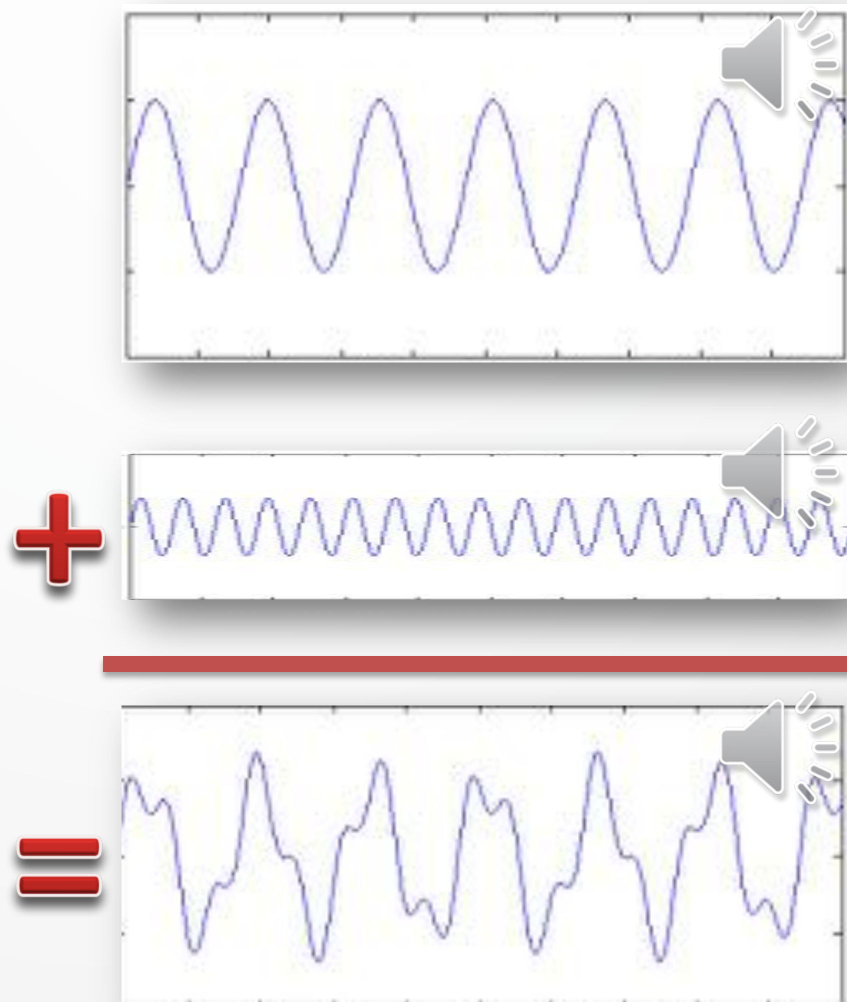
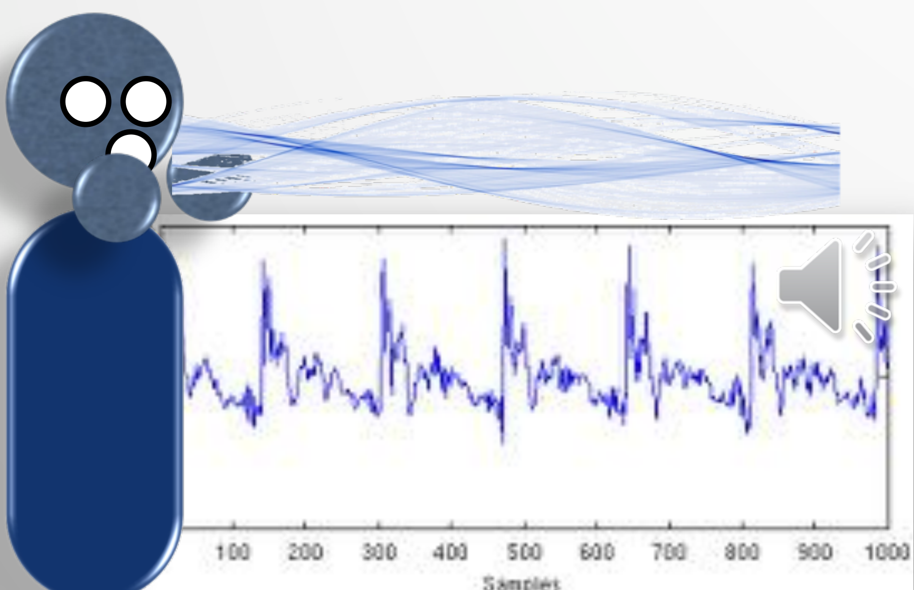
Superposition of sinusoids

- **Superposition**: *n.* the adding of sinusoids together.

- **Phase**: *n.* The horizontal offset of a sinusoid (ϕ).





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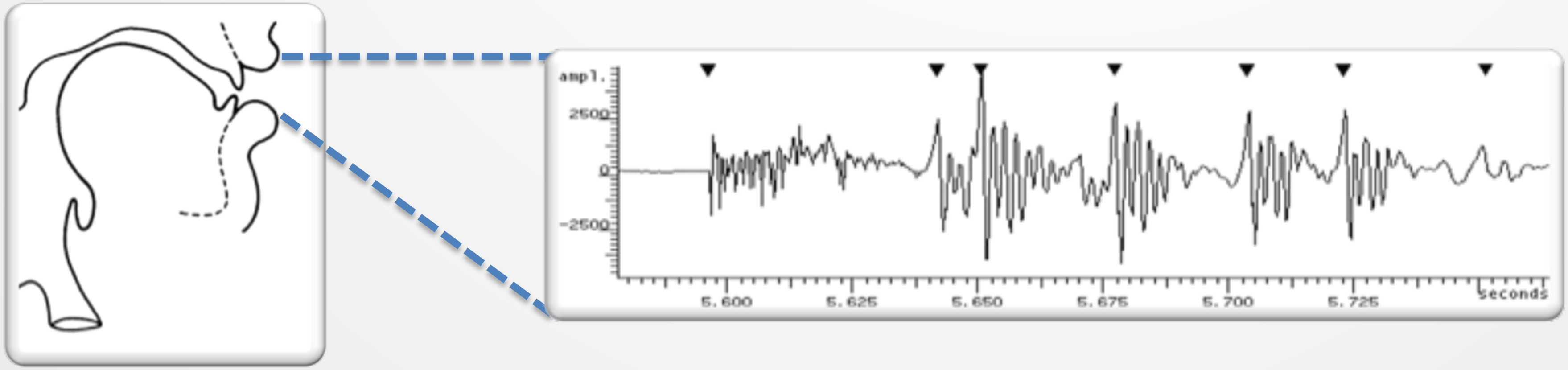
Extracting sinusoids from waveforms

- As we will soon see, the relative **amplitudes** and **frequencies** of the sinusoids that combine in speech are often **extremely indicative** of the speech units being uttered.
  - ∴ If we could **separate** the waveform into its component sinusoids, it would help us **classify** the speech being uttered.
  - *But the shape of the signal changes over time*

    (it's not a single repeating pattern)...



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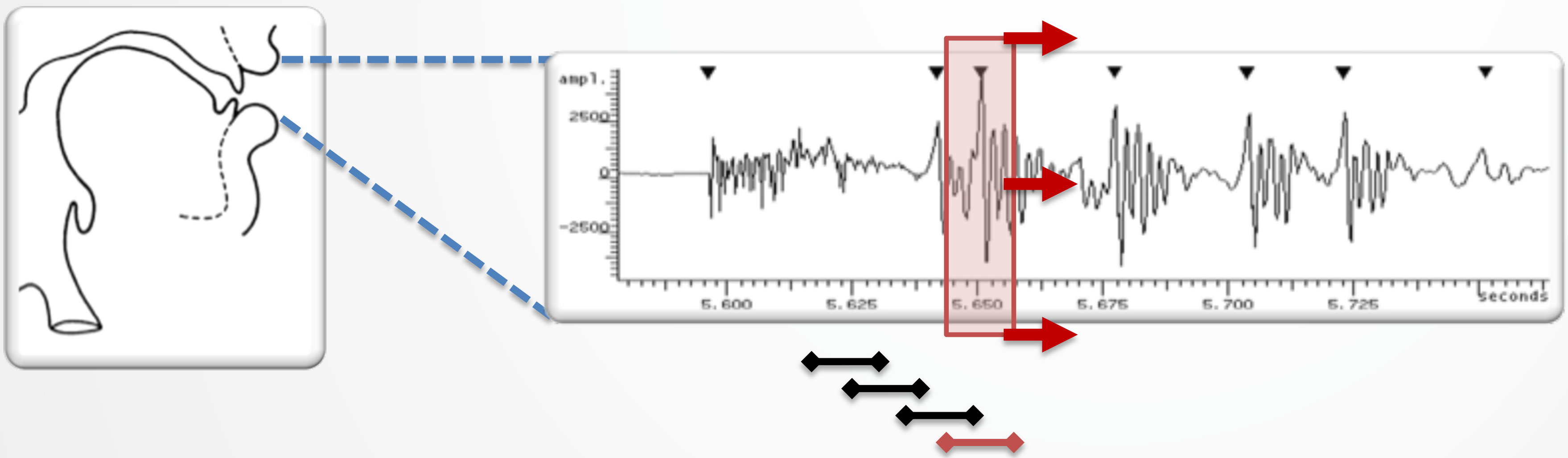
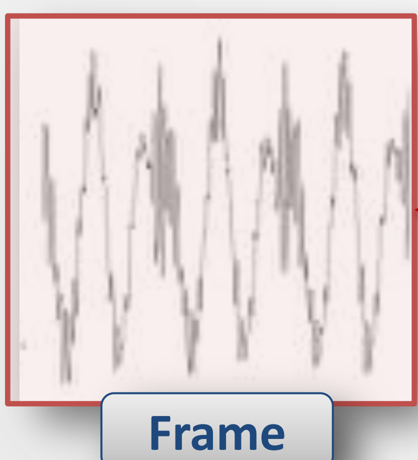
Short-time windowing





- Speech waveforms change drastically over time.
- We *move* a short analysis window (assumed to be time-invariant) across the waveform in time.
  - E.g. frame shift: 5—10 ms
  - E.g. frame length: 10—25 ms

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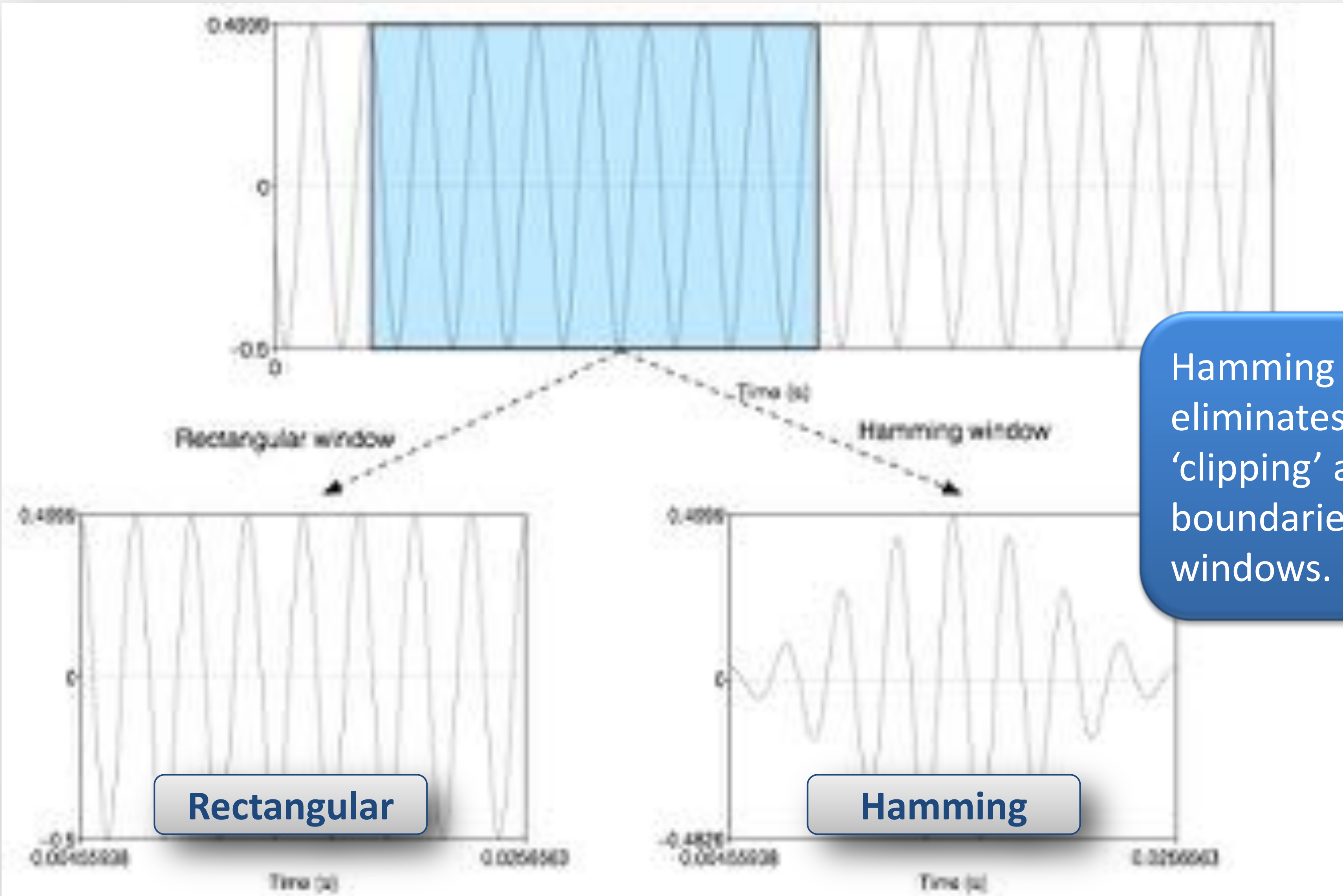
Window types



Hamming eliminates 'clipping' at the boundaries of windows.

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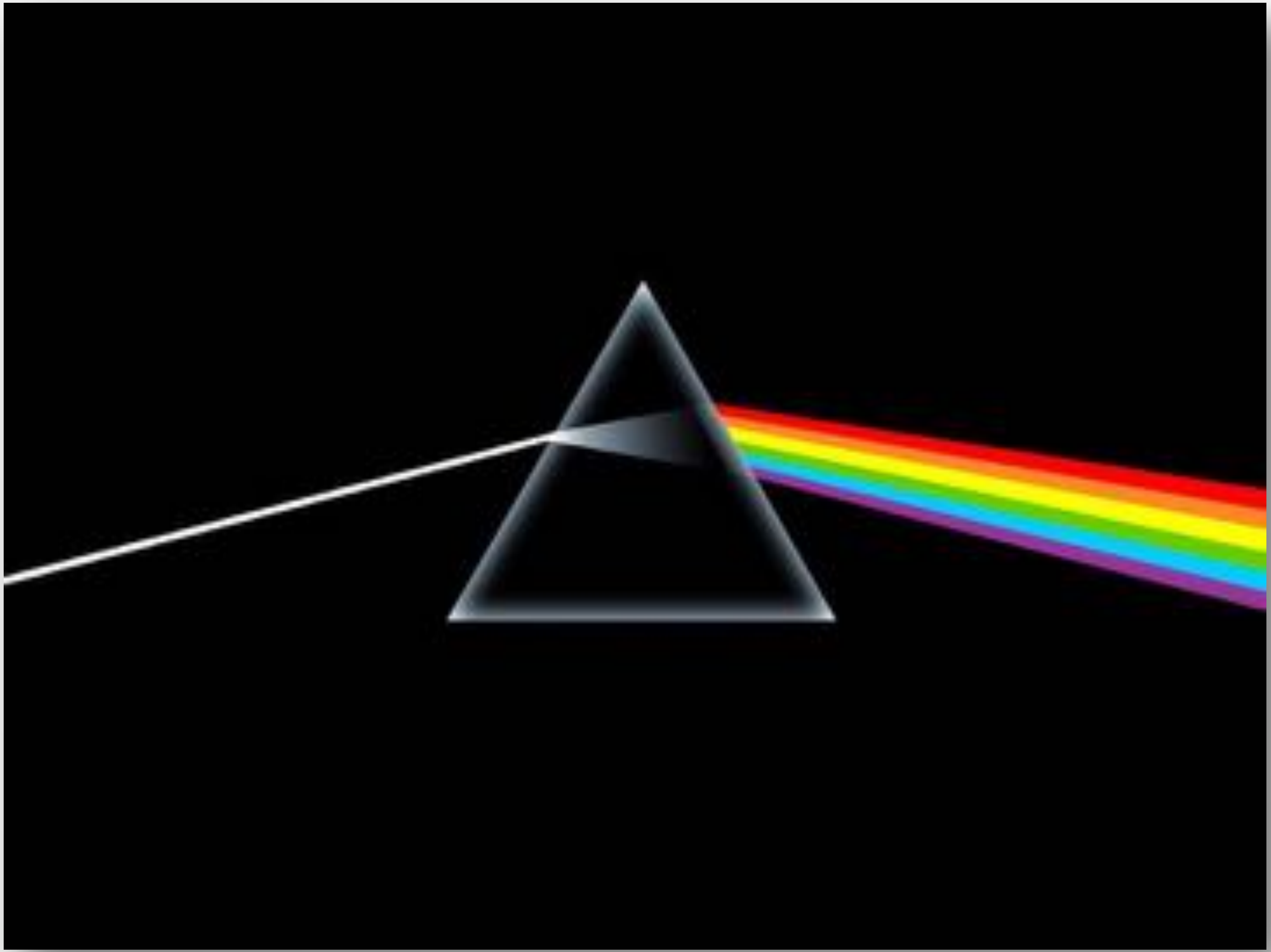
Extracting a spectrum

White light



Any Colour
You Like
(track 8)

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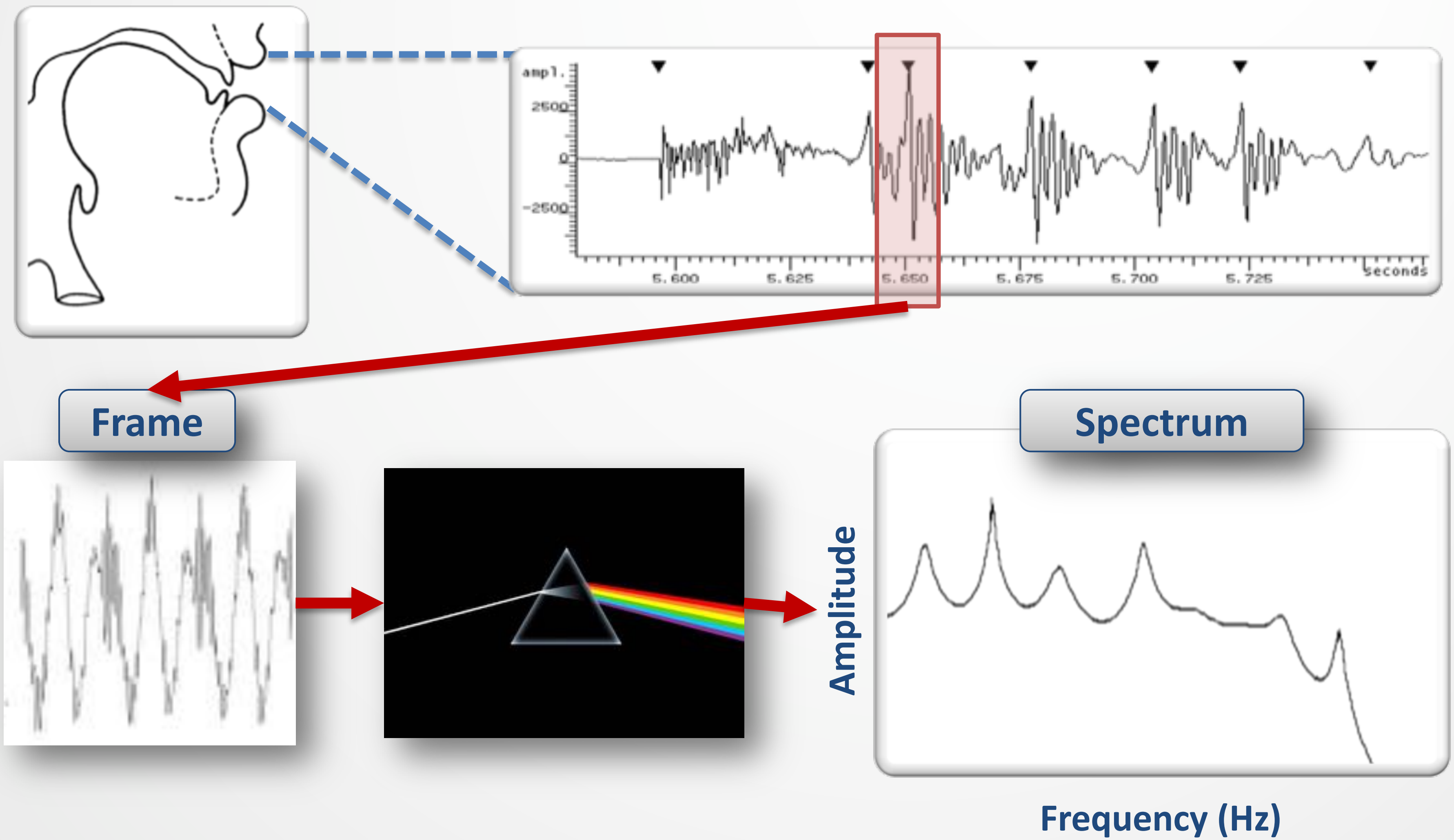
Extracting a spectrum in a window

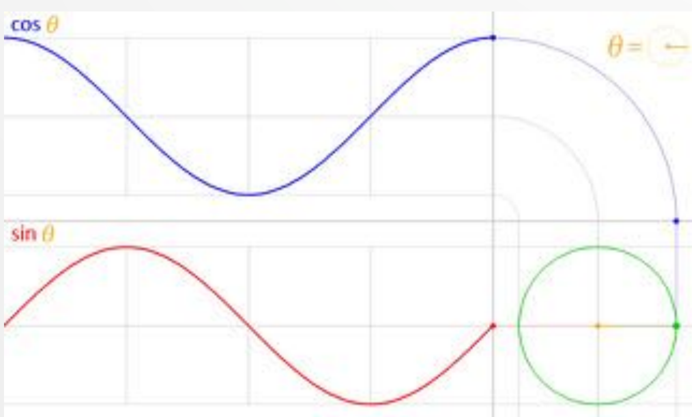


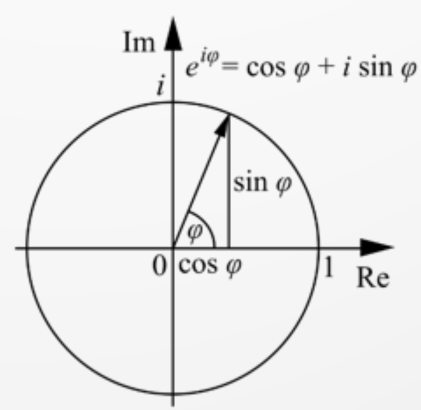
Aside – Euler's formula

- Extracting sinusoids uses a relationship between natural exponent e and sinusoids expressed in **Euler's formula:**

$$e^{ix} = \cos(x) + i\sin(x)$$

$$e^{i\pi} = -1$$





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The continuous Fourier transform

- **Input**: Continuous signal $x(t)$.
- **Output**: Spectrum $X(F)$

$$X(F) = \int_{-\infty}^{\infty} x(t) e^{-i2\pi Ft}\, dt$$

(No need to memorize these)

- It's **invertible**, i.e., $x(t) = \int_{-\infty}^{\infty} X(F) e^{i2\pi Ft}\, dF$.
- It's **linear**, i.e., for $a, b \in \mathbb{C}$,
  if $h(t) = ax(t) + by(t)$,
  then $H(F) = aX(F) + bY(F)$

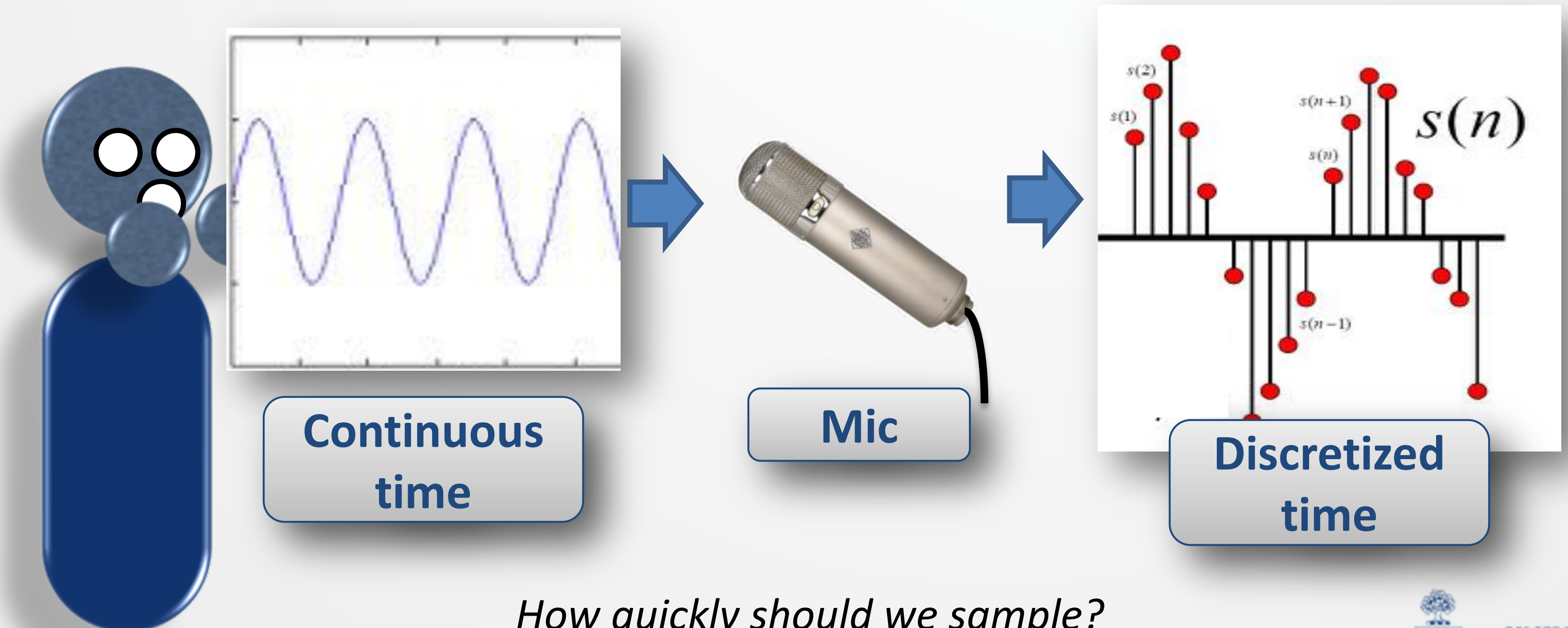
…

It needs **continuous** input $x(t)$… ***uh oh?***

Fun fact: Fourier instructed Champollion.

Discrete signal representation

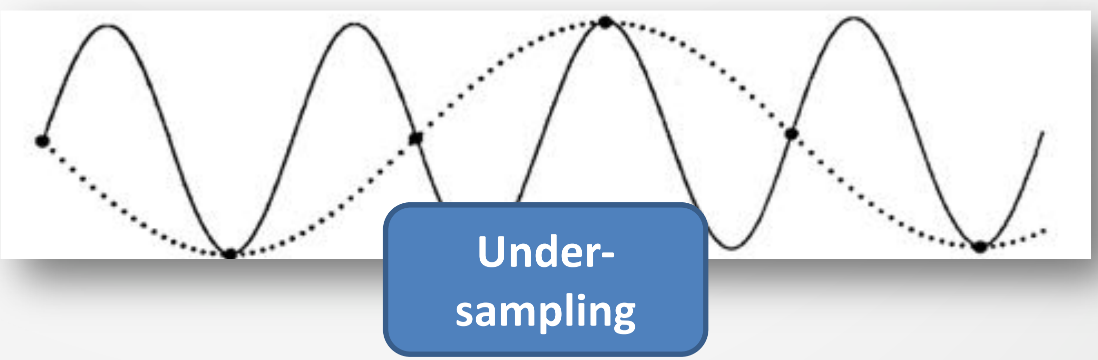
- **Sampling**: *vbg.* measuring the amplitude of a signal at regular intervals.
  - e.g., 44.1 kHz (*CD*), 8 kHz (*telephone*).
  - These amplitudes are initially measured as **continuous** values at **discrete** time steps.



How quickly should we sample?

Discrete signal representation

- **Nyquist rate**: *n.* the **minimum** sampling rate necessary to preserve a signal's **maximum** frequency.
  - i.e., **twice** the maximum frequency, since we need ≥ 2 samples/cycle.
  - Human speech is very informative ≤ 4 kHz, ∴ 8 kHz sampling.



Discrete Fourier transform (DFT)

- **Input**: Windowed signal $x[0] \ldots x[N-1]$.
- **Output**: N complex numbers $X[k] \;\; (k \in \mathbb{Z})$

(No need to memorize these)

$$X[k] = \sum_{n=0}^{N-1} x[n] e^{-i 2\pi k \frac{n}{N}}$$

- **Algorithm(s)**: the Fast Fourier Transform (FFT) with complexity $O(N \log N)$.
  - (Aside) The **Cooley-Tukey algorithm** *divides-and-conquers* by breaking the DFT into smaller ones $N = N_1 N_2$.

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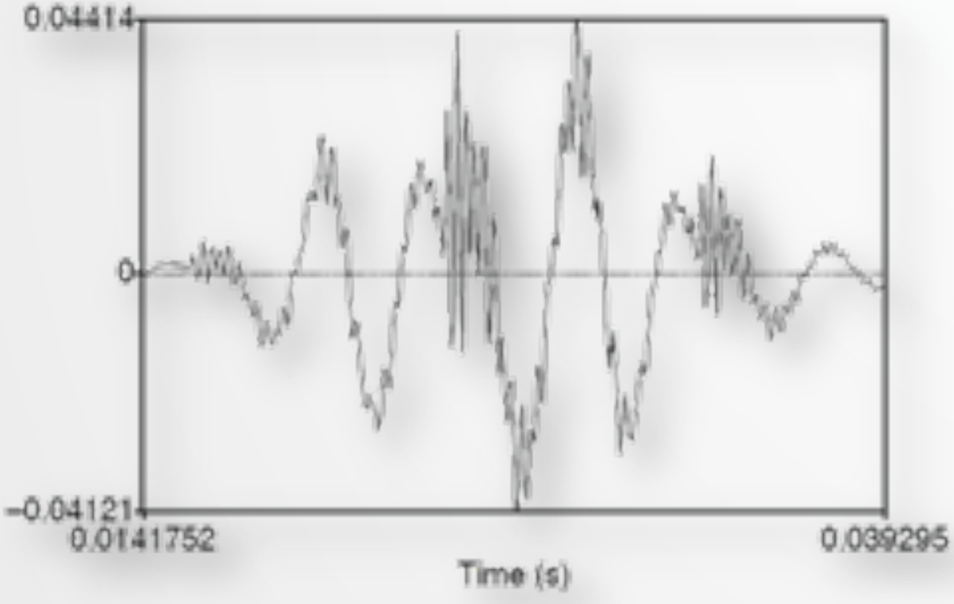
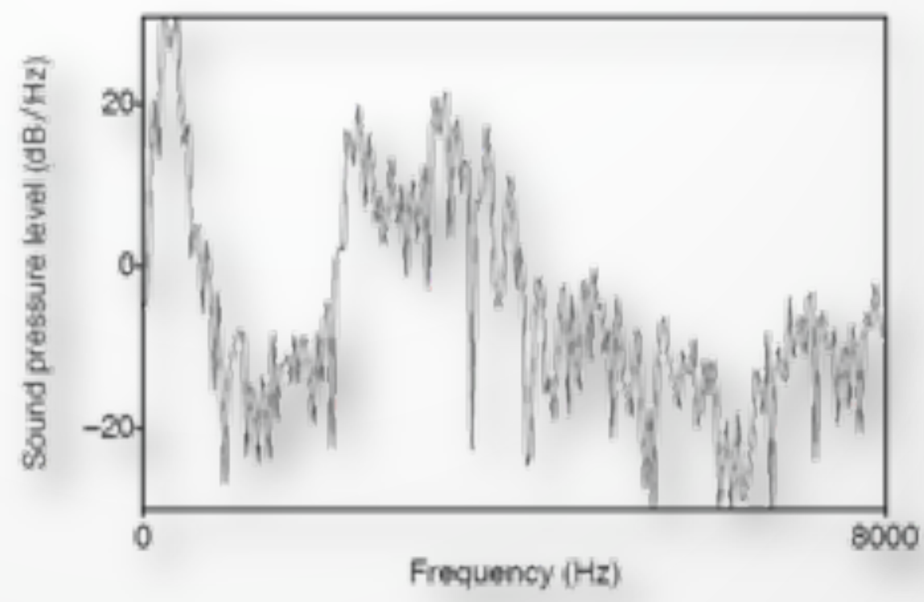
Discrete Fourier transform (DFT)

- Below is a 25 ms Hamming-windowed signal from /iy/ as in ‘bull sh***ee***p’, and its spectrum as computed by the DFT.



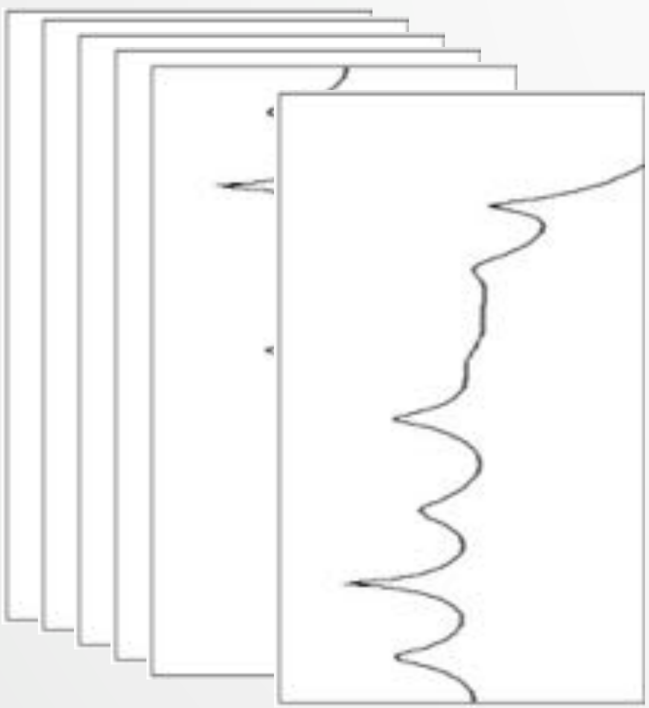


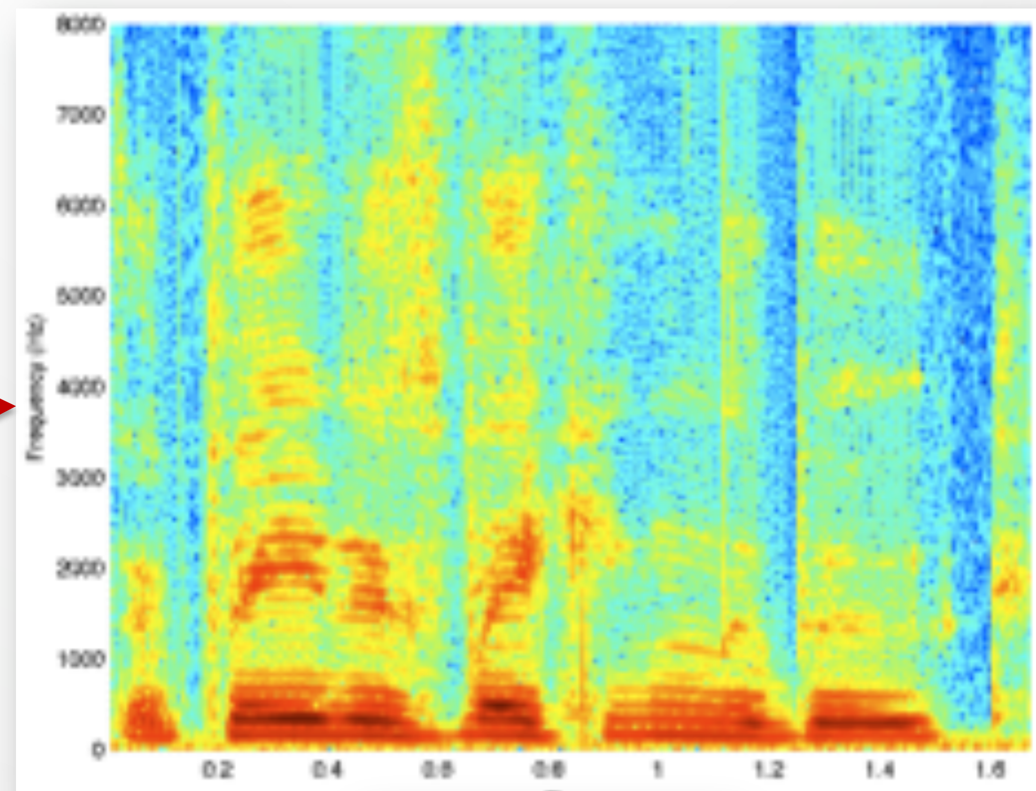
Recall: the Fourier transform is invertible

But this is all just for a small window…

Spectrograms

- **Spectrogram**: *n.* a 3D plot of **amplitude** and **frequency** over **time** (higher ‘redness’ → higher amplitude).





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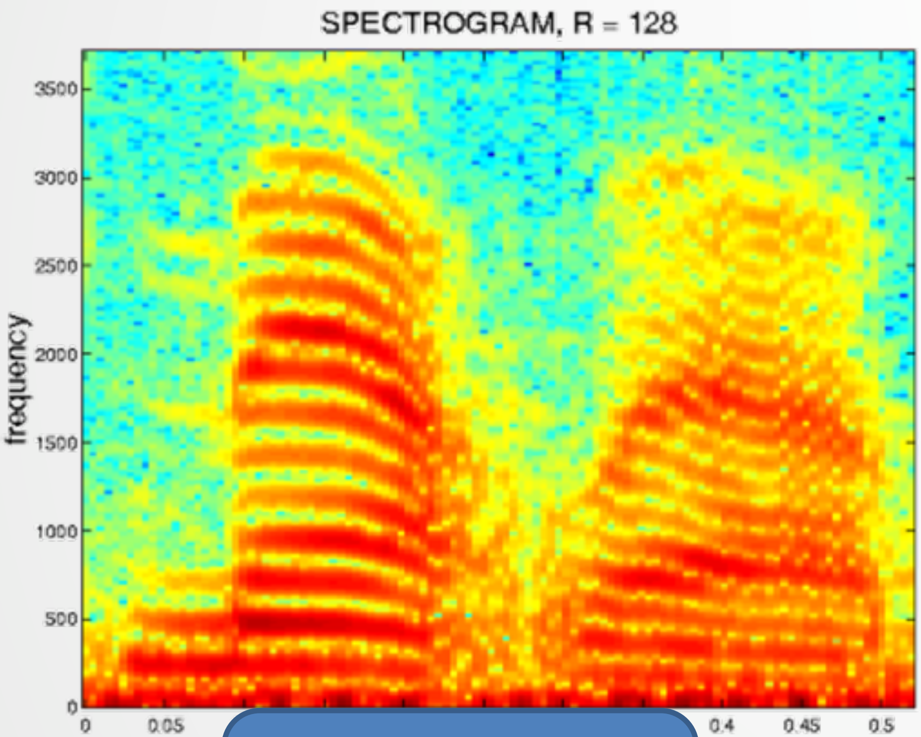
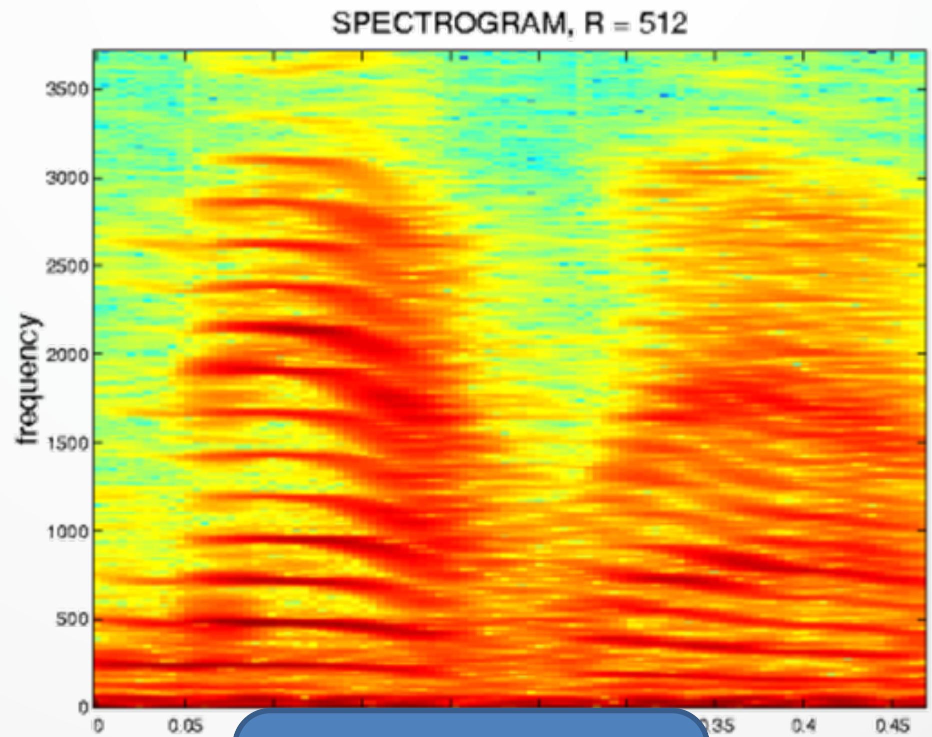
Effect of window length



Wide-band
(better time
resolution)



Narrow-band
(better frequency
resolution)

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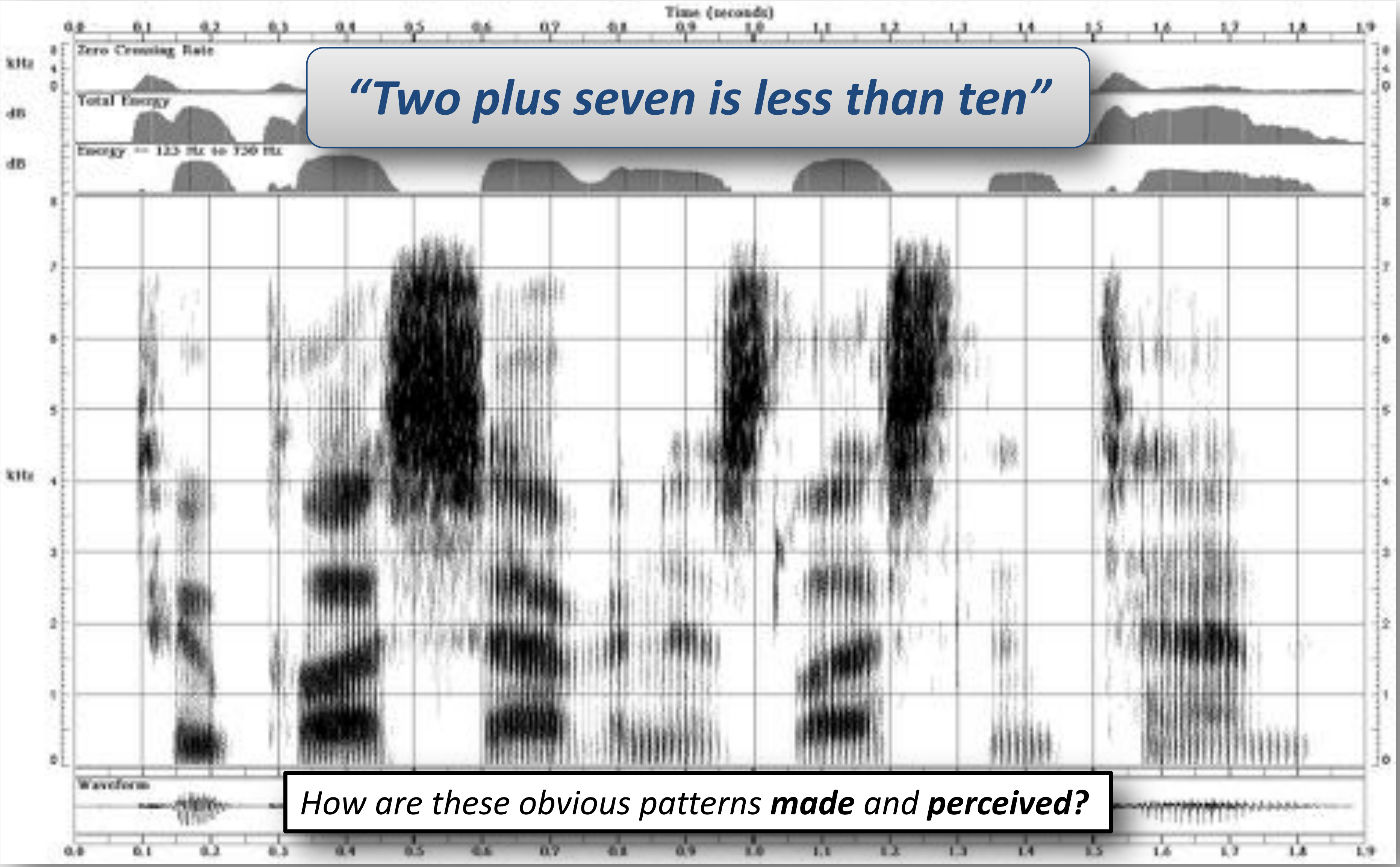
Spectrograms



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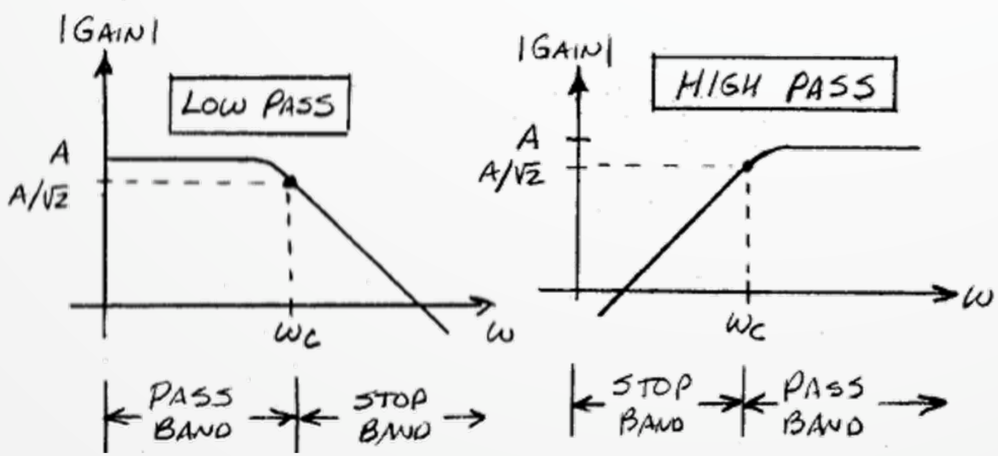
Aside – Filtering

- Sometimes you only want **part** of a signal.
  - E.g., you have measurements of lip aperture over time – you know that they can't move > 5-10 Hz.
  - E.g., you know there's some low-frequency Gaussian noise in either the environment or transmission medium.



- Low- and high-pass filters can be combined in series, yielding a **band-pass** filter.

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speech production

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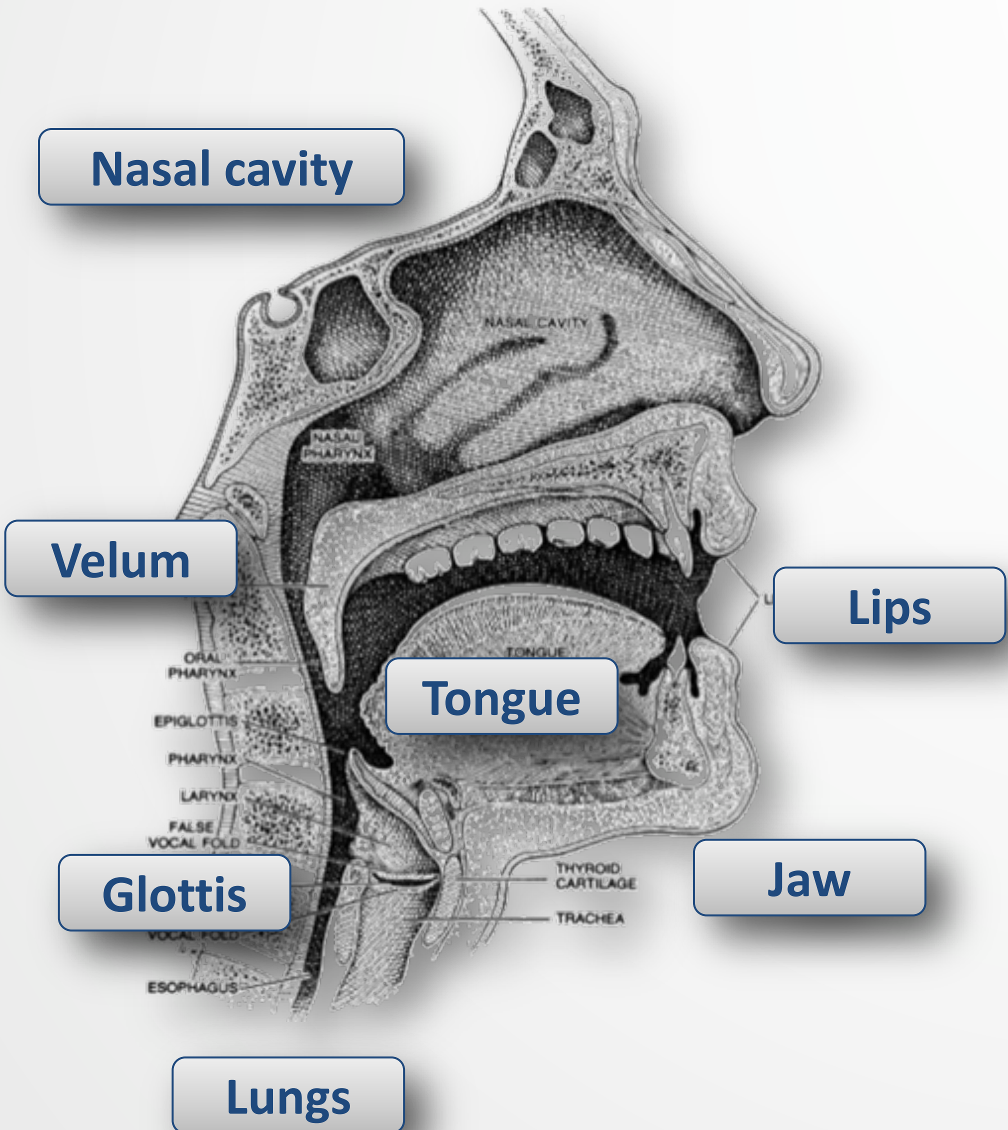
The vocal tract



- Many physical structures are co-ordinated in the production of speech.
- Generally, sound is **generated** by passing air through the vocal tract.
- Sound is **modified** by constricting airflow in particular ways.

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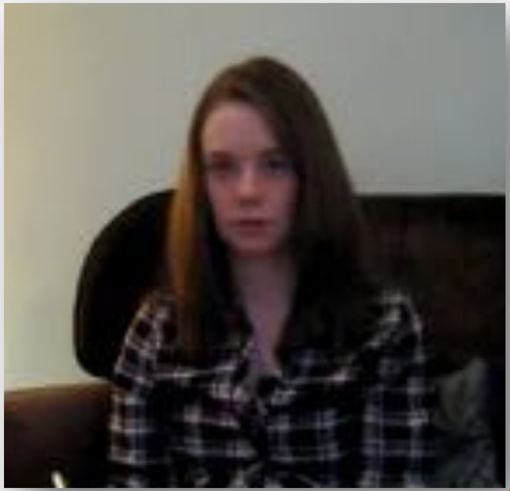
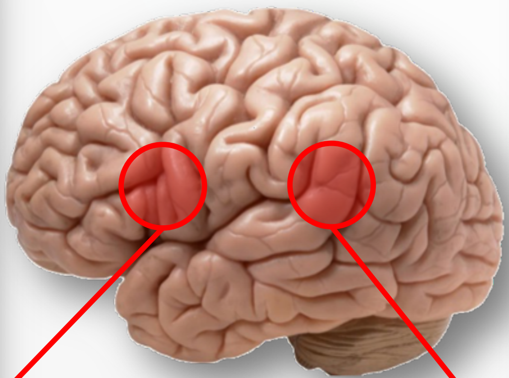
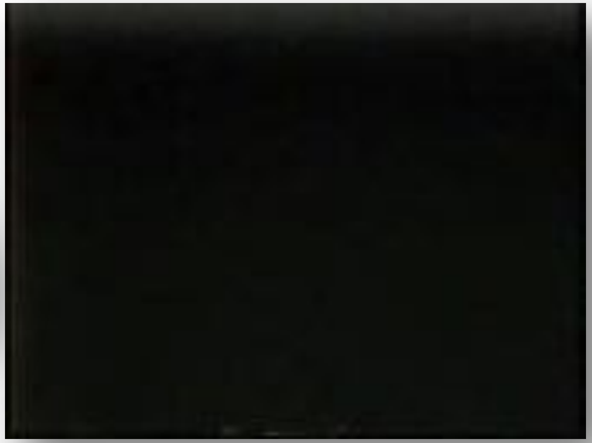
The neurological origins of speech

- Studying how systems break down can indicate how they work.







Broca's aphasia

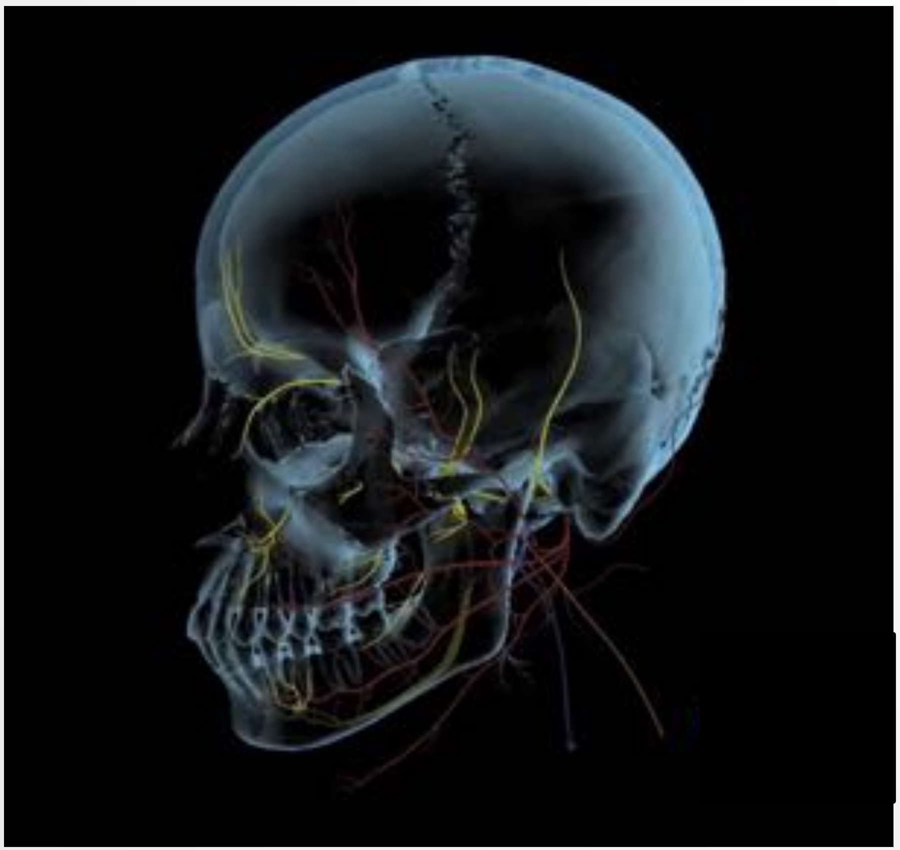
- **Reduced** hierarchical **syntax**.
- **Anomia**.
- **Reduced** "mirroring" between **observation** and **execution**.

Wernicke's aphasia

- **Normal** intonation/rhythm.
- **Meaningless** words.
- **'Jumbled'** syntax.
- **Reduced** comprehension.

The neurological origins of speech

- Cranial nerves carry messages from the brain to the various **articulators.**

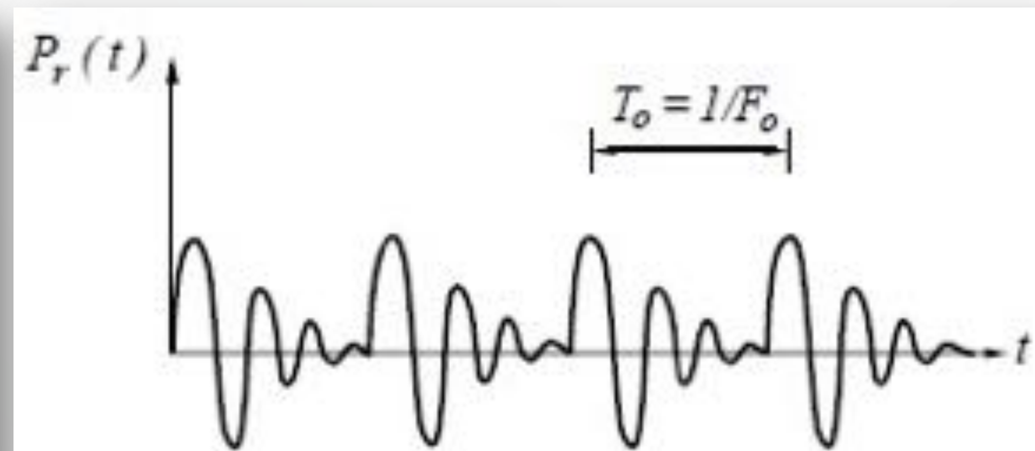


- Cranial nerves carry messages from the brain to the various **articulators.**
  - **Damage** to these nerves can result in **neuro-motor** disorders such as cerebral palsy.
  - These may be another example of the noisy channel.

Fundamental frequency

- F_0: *n.* (**fundamental frequency**), the rate of vibration of the **glottis** – often very **indicative** of the speaker.

Glottis



	Avg F_0 (Hz)	Min F_0 (Hz)	Max F_0 (Hz)
Men	125	80	200
Women	225	150	350
Children	300	200	500

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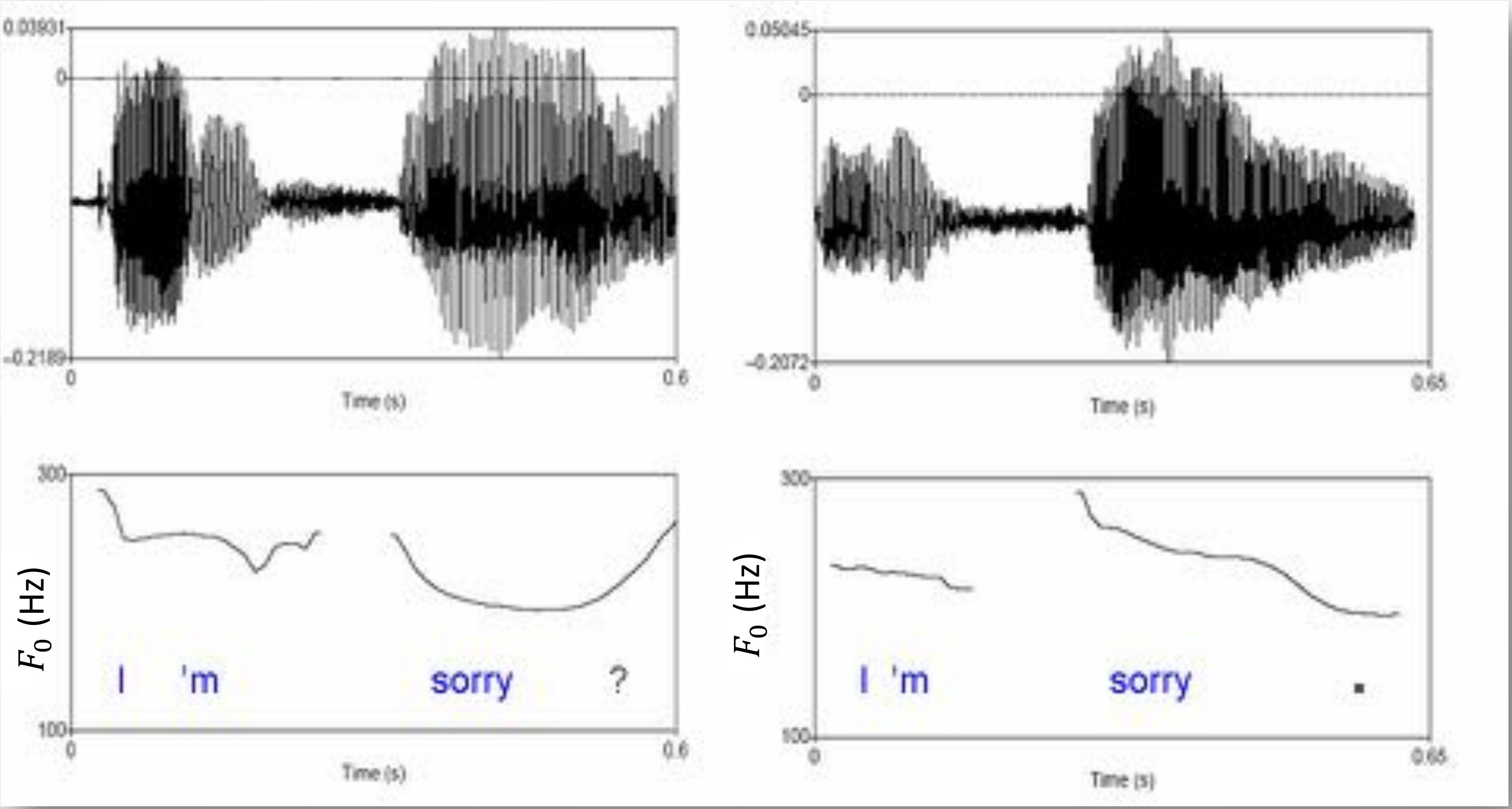
Prosody

- **Sonorant**: *n.* Any **sustained** sound in which the **glottis** is vibrating (i.e., the sound is '**voiced**').
  - Includes some consonants (e.g., */w/*, */m/*).

- **Prosody**: *n.* the **modification** of speech acoustics in order to convey some **extra-lexical** meaning:
  - **Pitch**: Changing of F_0 over time.
  - **Duration**: The length in time of sonorants.
  - **Loudness**: The amount of **energy** produced by the **lungs**.

Pitch prosody example



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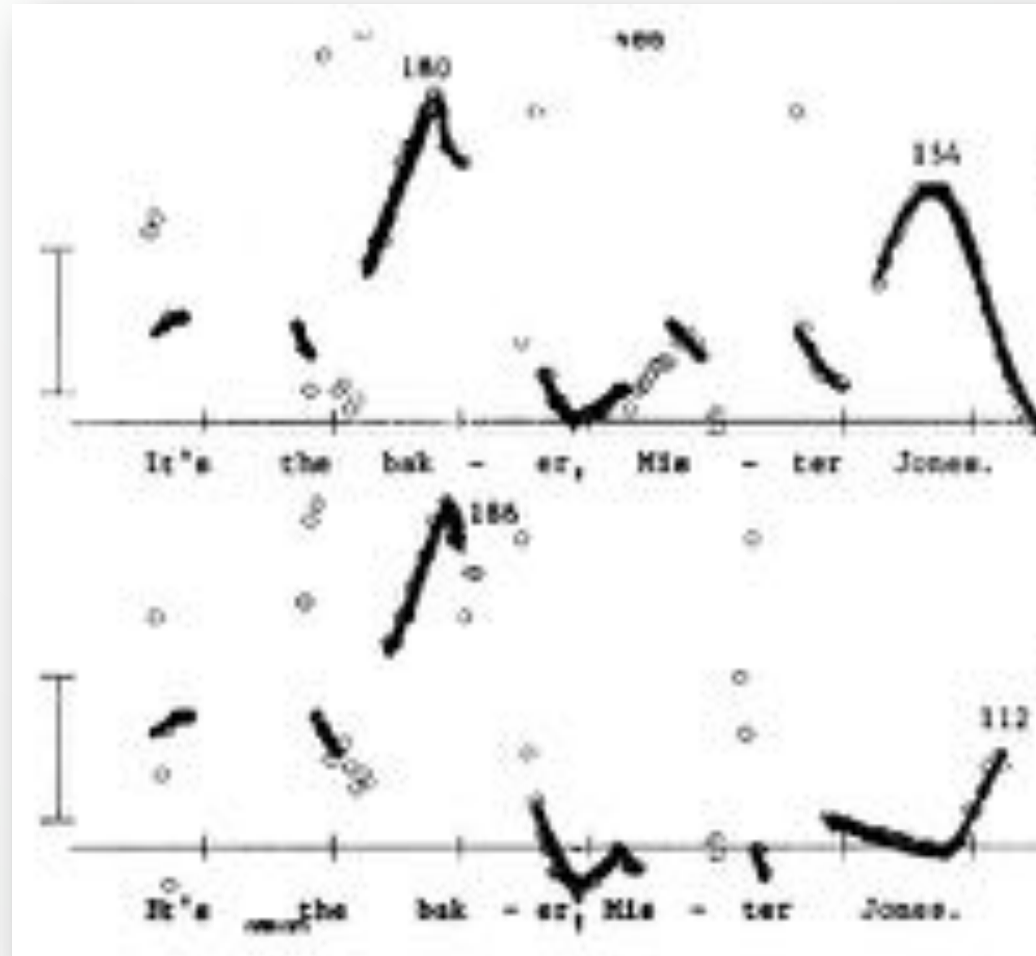
Pitch can modify meaning

- e.g., I ask you
  "who is that?"



- e.g., I ask you
  "what is his job?"

Pitch tends to rise when uttering novel or important information.

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Pitch can modify meaning

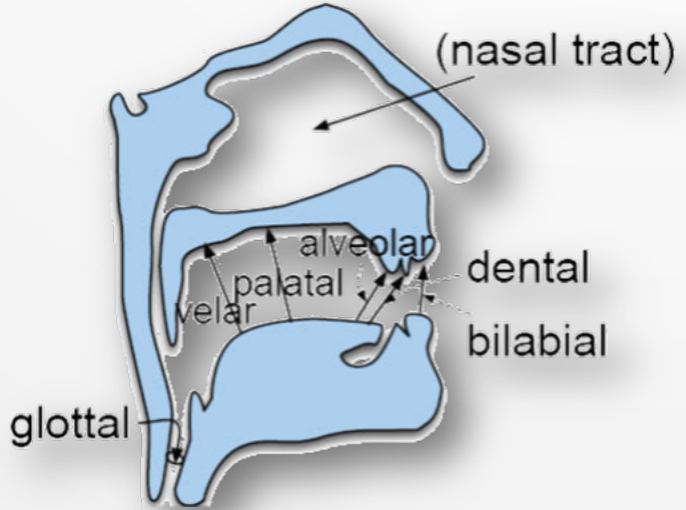
- ***I*** never said she stole my money. (Someone else said it)
- I ***never*** said she stole my money. (It never happened)
- I never ***said*** she stole my money. (I just hinted at it)
- I never said ***she*** stole my money. (Someone else stole it)
- I never said she ***stole*** my money. (She just borrowed it)
- I never said she stole ***my*** money. (She stole someone else's)
- I never said she stole my ***money***. (She stole my heart).

Phonemes

- **Phoneme**: *n.* a distinctive unit of speech sound.
- Phonemes can be partitioned into **manners of articulation**:
  - **Vowels**: **open** vocal tract, no nasal air.
  - **Fricatives:** **noisy**, with air passing through a tight constriction (e.g., '*shift*').
  - **Stops/plosives:** **complete** vocal tract constriction and burst of energy (e.g., '*papa*').
  - **Nasals**: air passes through the **nasal** cavity (e.g., '*mama*').
  - **Semivowels**: similar to vowels, but typically with more constriction (e.g., '*wall*').
  - **Affricates**: Alveolar stop followed by fricative.

Place of articulation

- The **location** of the *primary constriction* can be:
  - **Alveolar**: constriction near the alveolar ridge (e.g., /*t*/)
  - **Bilabial**: touching of the lips together (e.g., /*m*/, /*p*/)
  - **Dental**: constriction of/at the teeth (e.g., /*th*/)
  - **Labiodental**: constriction between lip and teeth (e.g., /*f*/)
  - **Velar**: constriction at or near the velum (e.g., /*k*/).



Phonemic alphabets

- There are several alphabets that categorize the sounds of speech.
  - The **International Phonetic Alphabet (IPA)** is popular, but it uses non-ASCII symbols.
  - The **TIMIT** phonemic alphabet will be used by **default** in this course.

  - Other popular alphabets include **ARPAbet**, **Worldbet**, and **OGIbet**, usually adding special cases.
    - E.g., /pcl/ is the period of silence immediately before a /p/.

TIMIT	IPA	e.g.
/iy/	/iʸ/	*beat*
/ih/	/ɪ/	*bit*
/eh/	/ɛ/	*bet*
/ae/	/æ/	*bat*
/aa/	/ɑ/	*Bob*
/ah/	/ʌ/	*but*
/ao/	/ɔ/	*bought*
/uh/	/ʊ/	*book*
/uw/	/u/	*boot*
/ux/	/ʉ/	*suit*
/ax/	/ə/	*about*

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TIMIT Phonemic alphabet (incomplete)

Vowel	e.g.
/iy/	*beat*
/ih/	*bit*
/eh/	*bet*
/ae/	*bat*
/aa/	*Bob*
/ah/	*but*
/ao/	*bought*
/uh/	*book*
/uw/	*boot*
/ux/	*suit*
/ax/	*about*

stop	e.g.
/b/	*Bilbo*
/d/	*dada*
/g/	*Gaga*
/p/	*Pippin*
/t/	*Toots*
/k/	*kick*

nasal	e.g.
/m/	*Mama*
/n/	*noon*
/ng/	*thing*

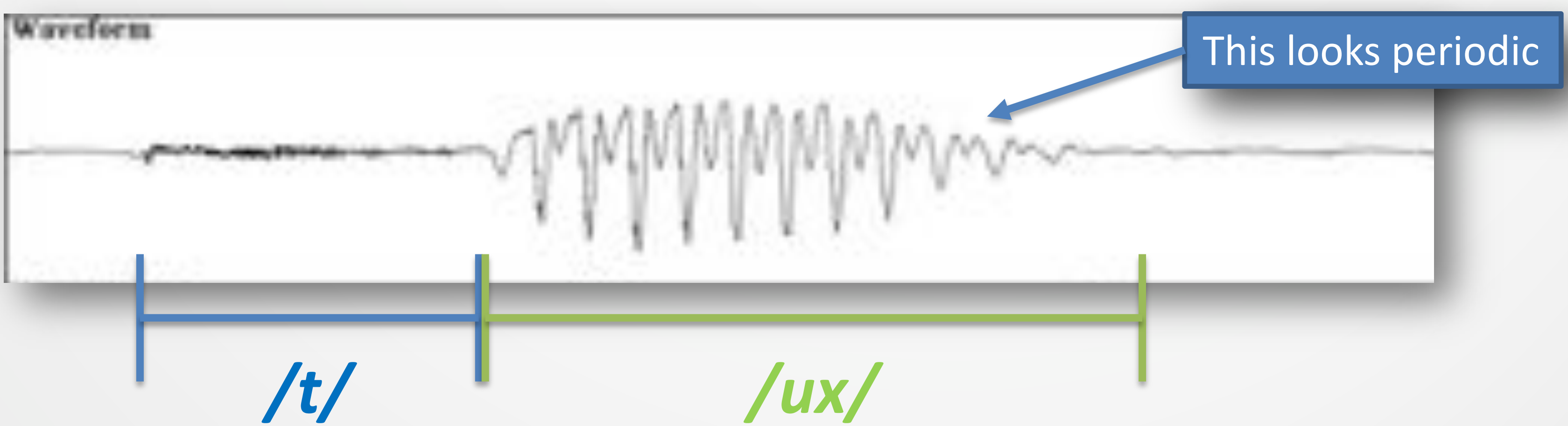
fricative	e.g.
/s/	*Sea*
/f/	*Frank*
/z/	*Zappa*
/th/	*this*
/sh/	*Ship*
/zh/	*azure*
/v/	*Vogon*
/dh/	*then*

…

(Incomplete)

Phoneme sequences

- Often, we assume that a **spoken utterance** can be **partitioned** into a **sequence** of **non-overlapping** phonemes.
  - Demarking the periods during which certain phonemes are being uttered is called **transcription** or **annotation** (*).
  - This approach has problems (e.g., when *exactly* does one phoneme end and another begin?), but it's useful for **classification**.



*What are some characteristics of the six **manners** of articulation?*

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Vowels (1/6)

- There are approximately **19** vowels in Canadian English, including **diphthongs** in which the articulators **move** over time.
- Vowels are distinguished primarily by their **formants**. (?)

Monophthong	e.g.
/iy/	*beat*
/ih/	*bit*
/eh/	*bet*
/ae/	*bat*
/aa/	*Bob*
/ao/	*bought*
/ah/	*but*
/uh/	*book*
/uw/	*boot*
/ax/	*about*
/ix/	*roses*

diphthong	e.g.
/ey/	*bait*
/ow/	*boat*
/ay/	*bite*
/oy/	*boy*
/aw/	*bout*
/ux/	*suit*

other	e.g.
/er/	*Bert*
/axr/	*butter*

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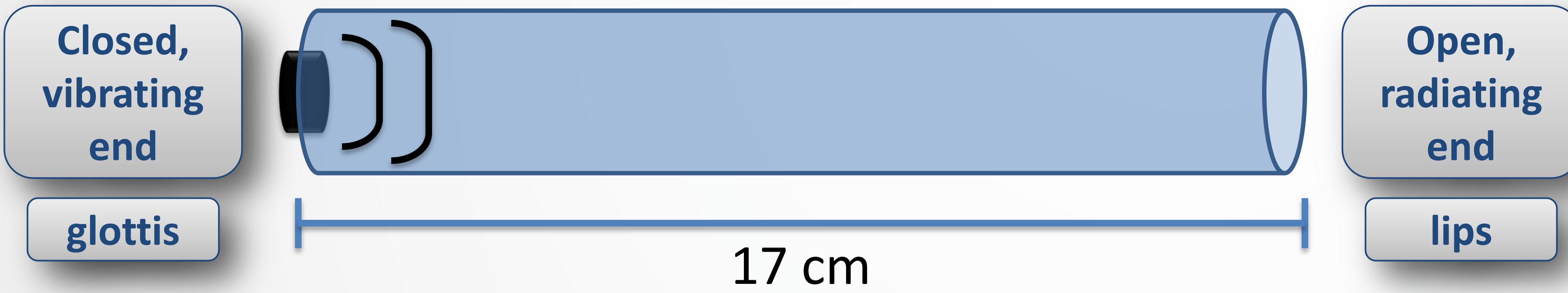
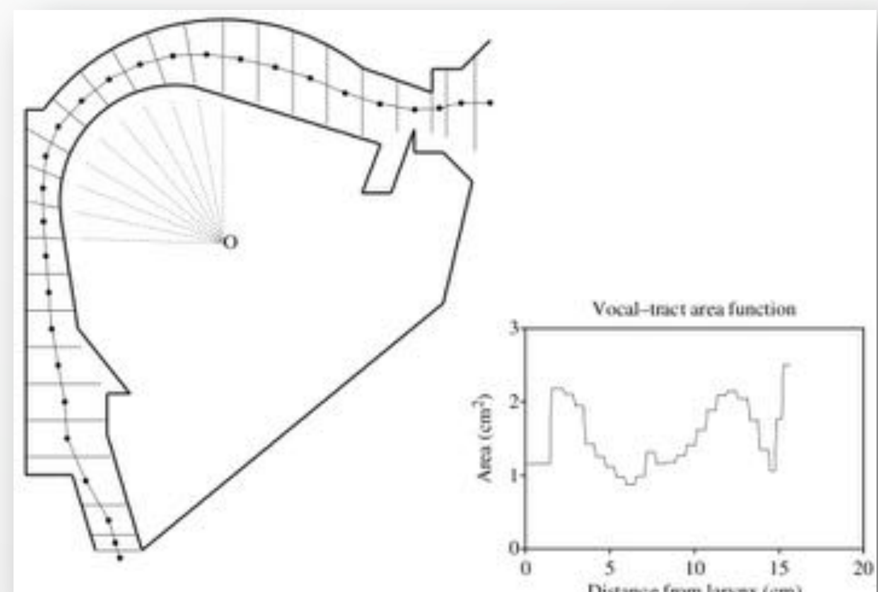
The uniform tube



- The positions of the tongue, jaw, and lips change the **shape** and **cross-sectional** area of the vocal tract.



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Uniform tubes in practice

- Many **musical instruments** are based on the idea of uniform (or, in many cases, bent) tubes.

- **Longer** tubes produce '**deeper**' sounds (lower frequencies).
    - A tube ½ the length of another will be 1 octave higher.

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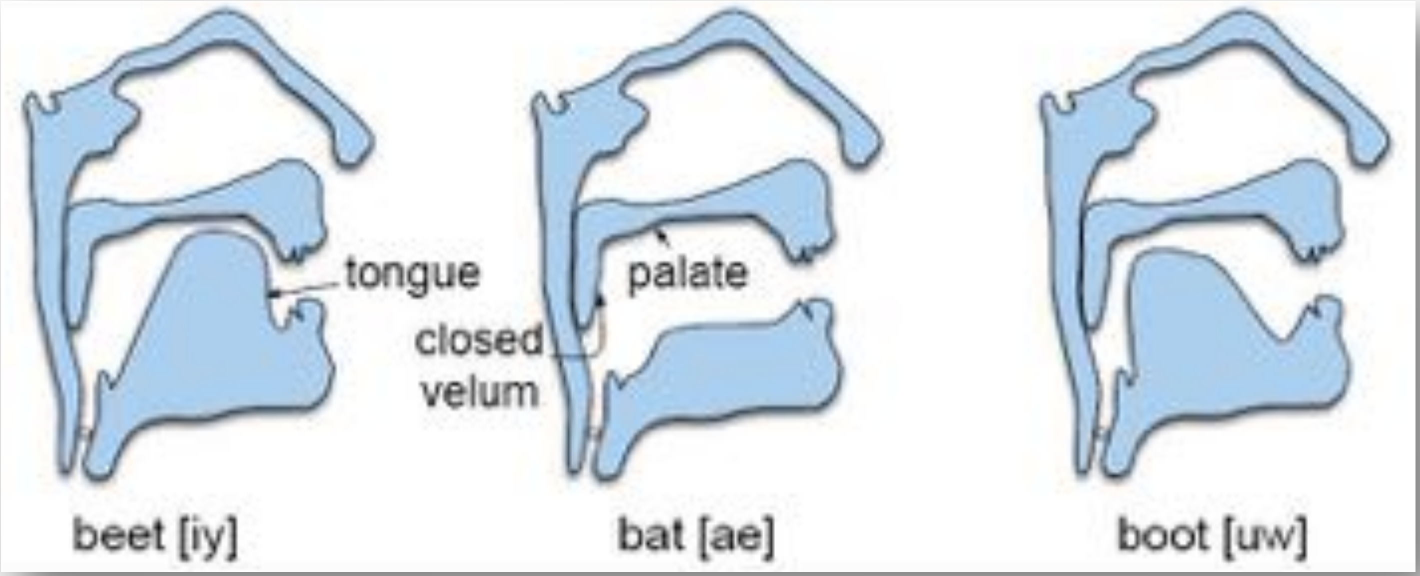
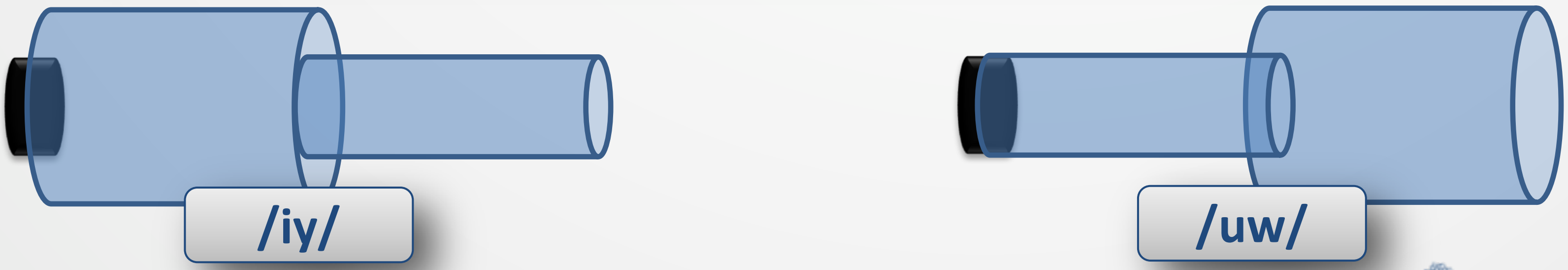
Vowels as concatenated tubes

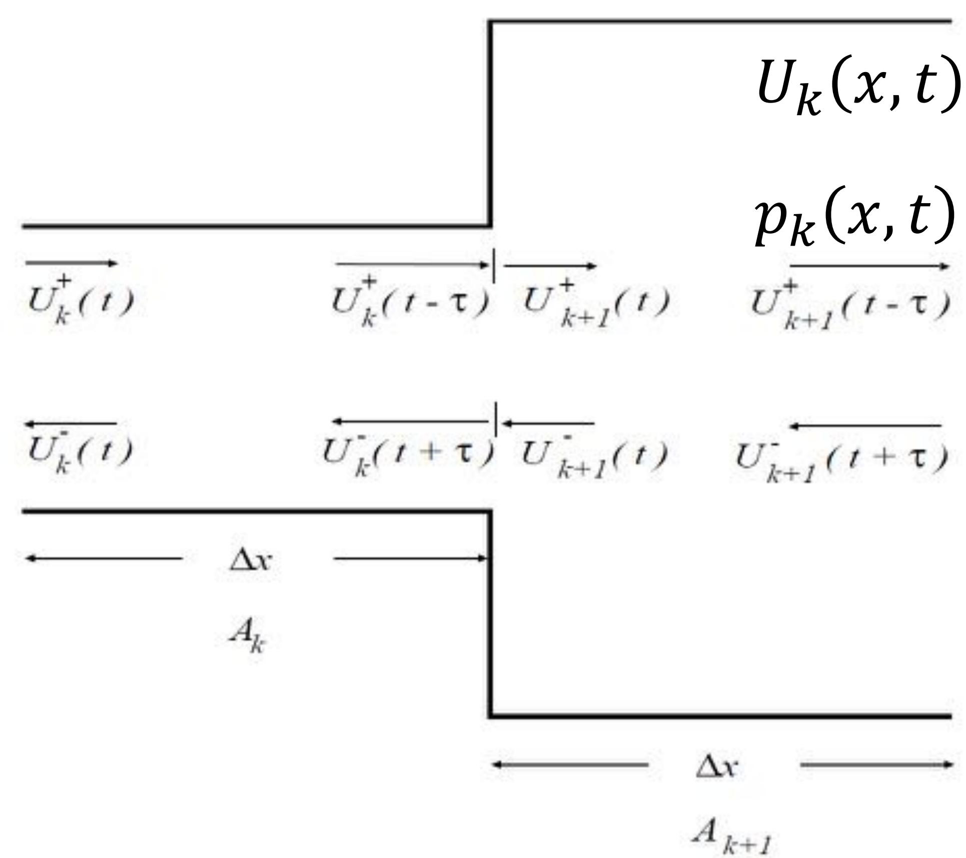
- The vocal tract can be modelled as the concatenation of dozens, hundreds, or thousands of tubes.





Aside – waves in concatenated tubes

- We model the **volume velocity** U_k and the **pressure variation** p_k at position x in the k^{th} lossless tube (whose area is A_k) at time t



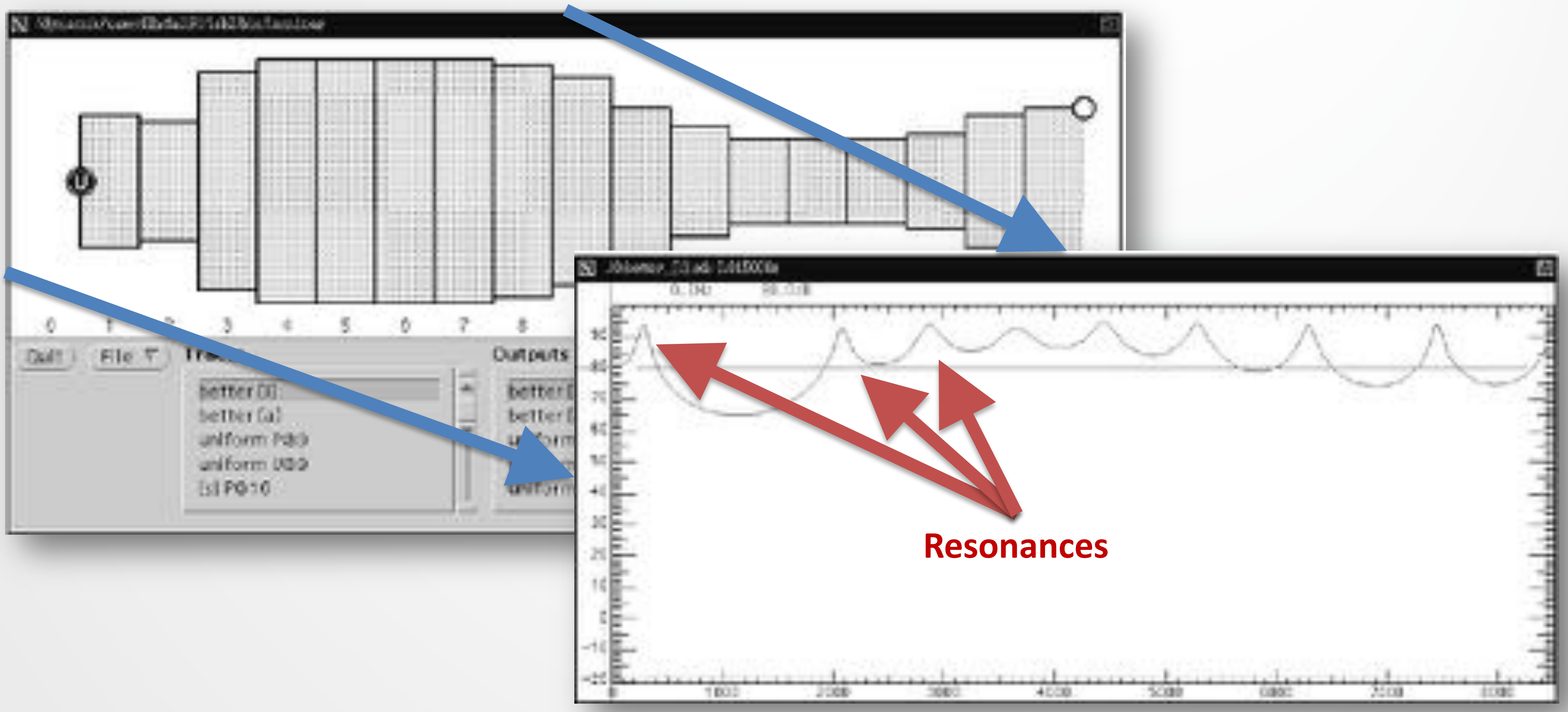
$$U_k(x,t) = U_k^+\left(t-\frac{x}{c}\right) - U_k^-\left(t+\frac{x}{c}\right)$$

$$p_k(x,t) = \frac{\rho c}{A_k}\left[U_k^+\left(t-\frac{x}{c}\right) + U_k^-\left(t+\frac{x}{c}\right)\right]$$

where
c is the speed of sound,
ρ is the density of air.

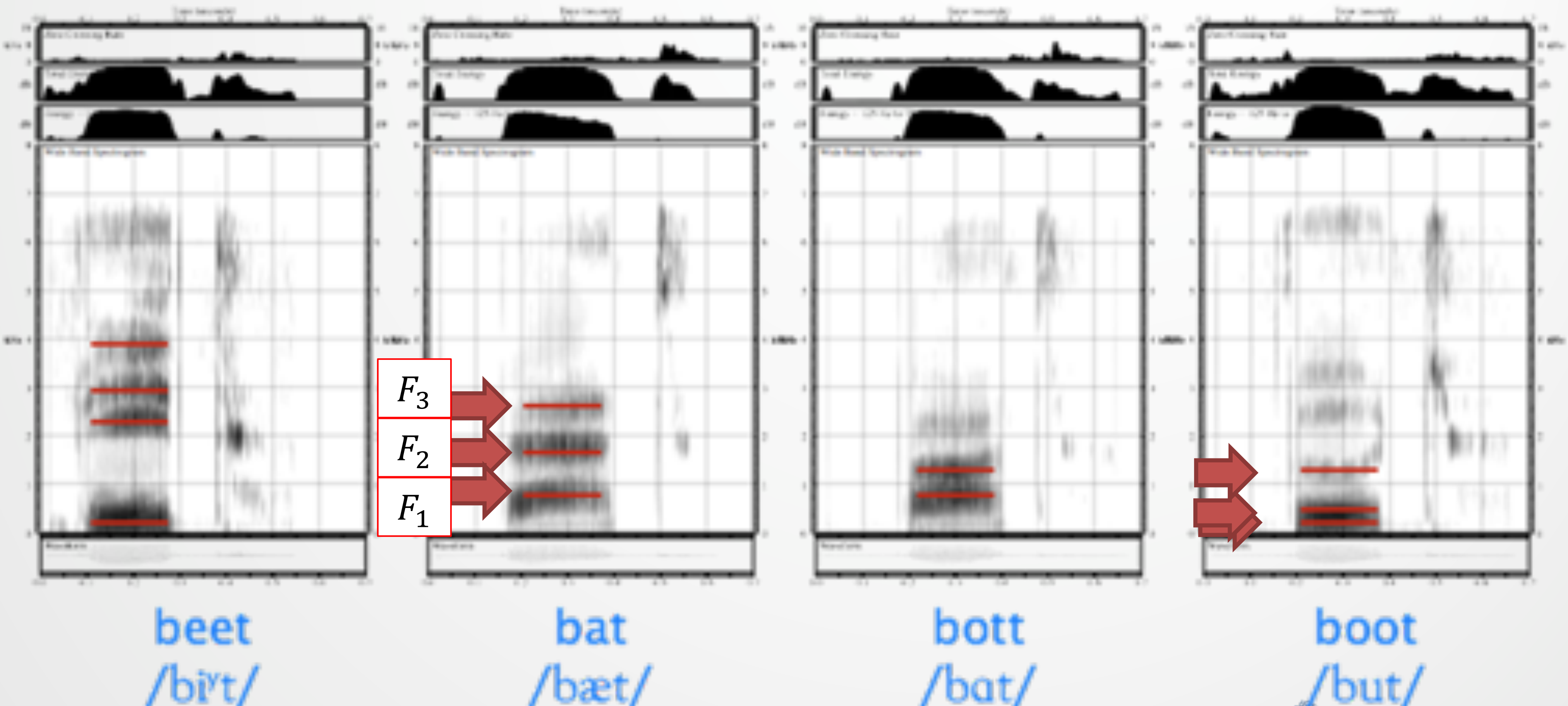
Waves in concatenated tubes

- Because of partial wave **reflections** that occur at tube boundaries, we can generate spectra with particular **resonances**.

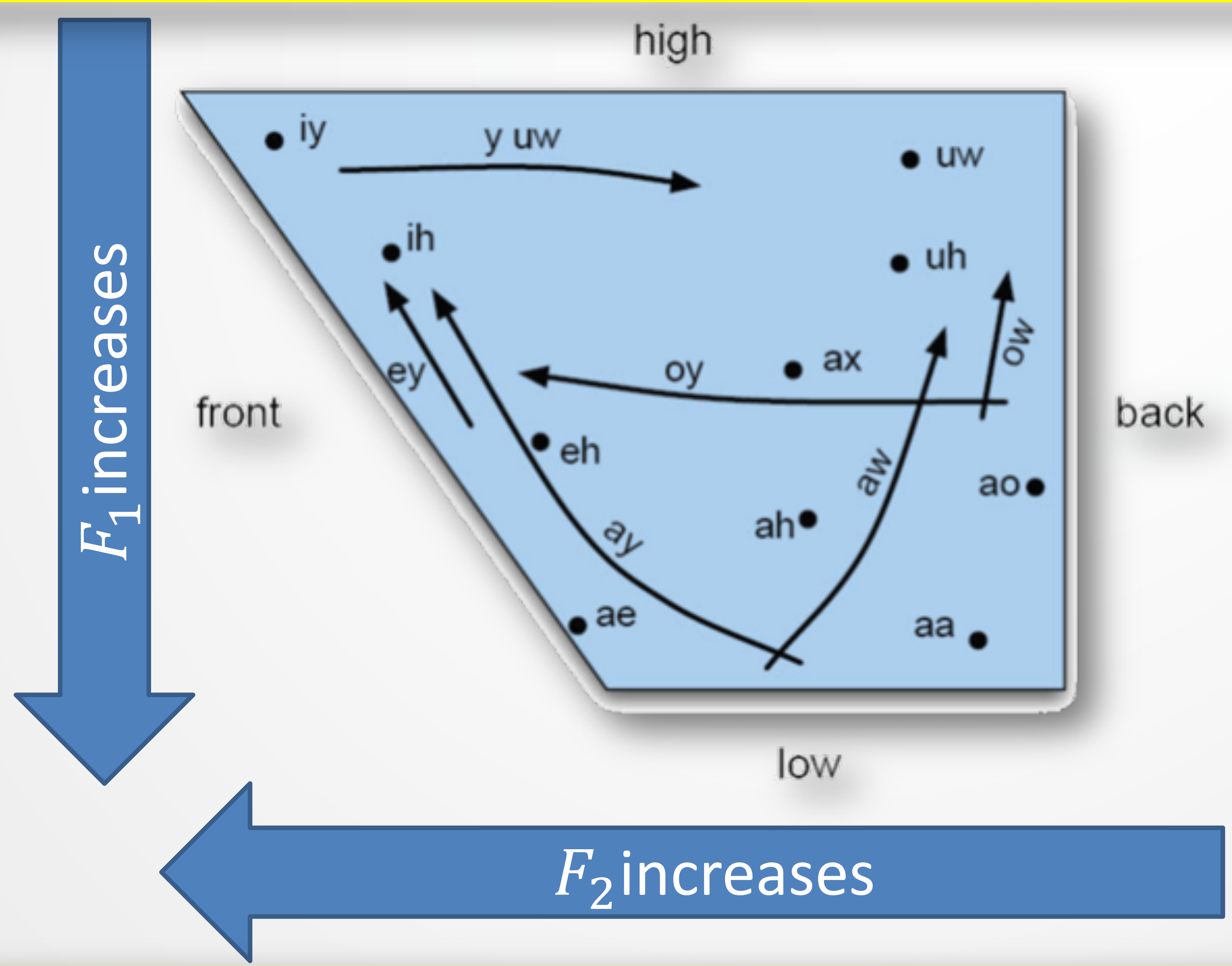


Formants and vowels

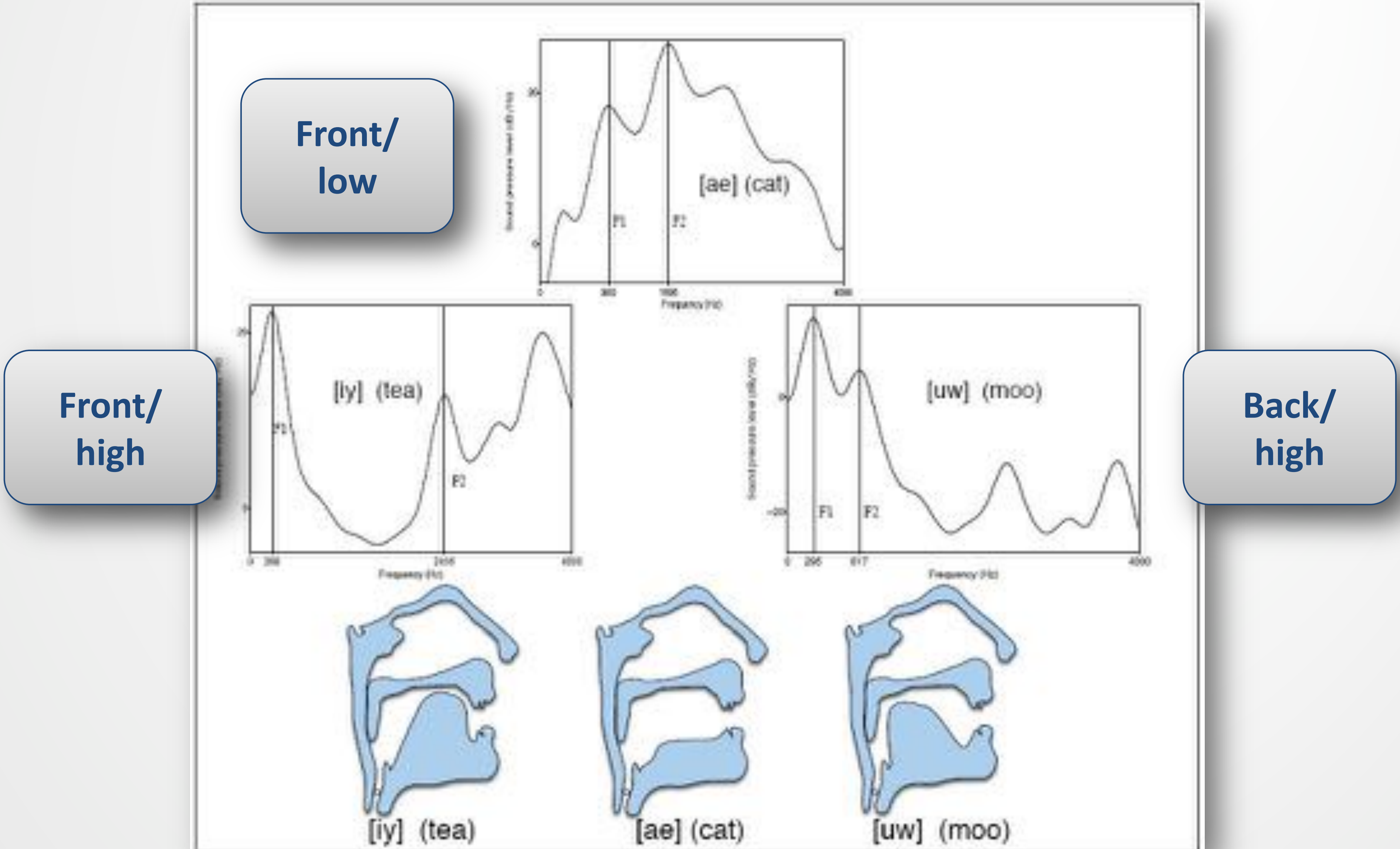
- **Formant:** *n.* A concentration of energy within a frequency band. Ordered from low to high bands (e.g., F_1, F_2, F_3).



The vowel trapezoid



Tongues and formants



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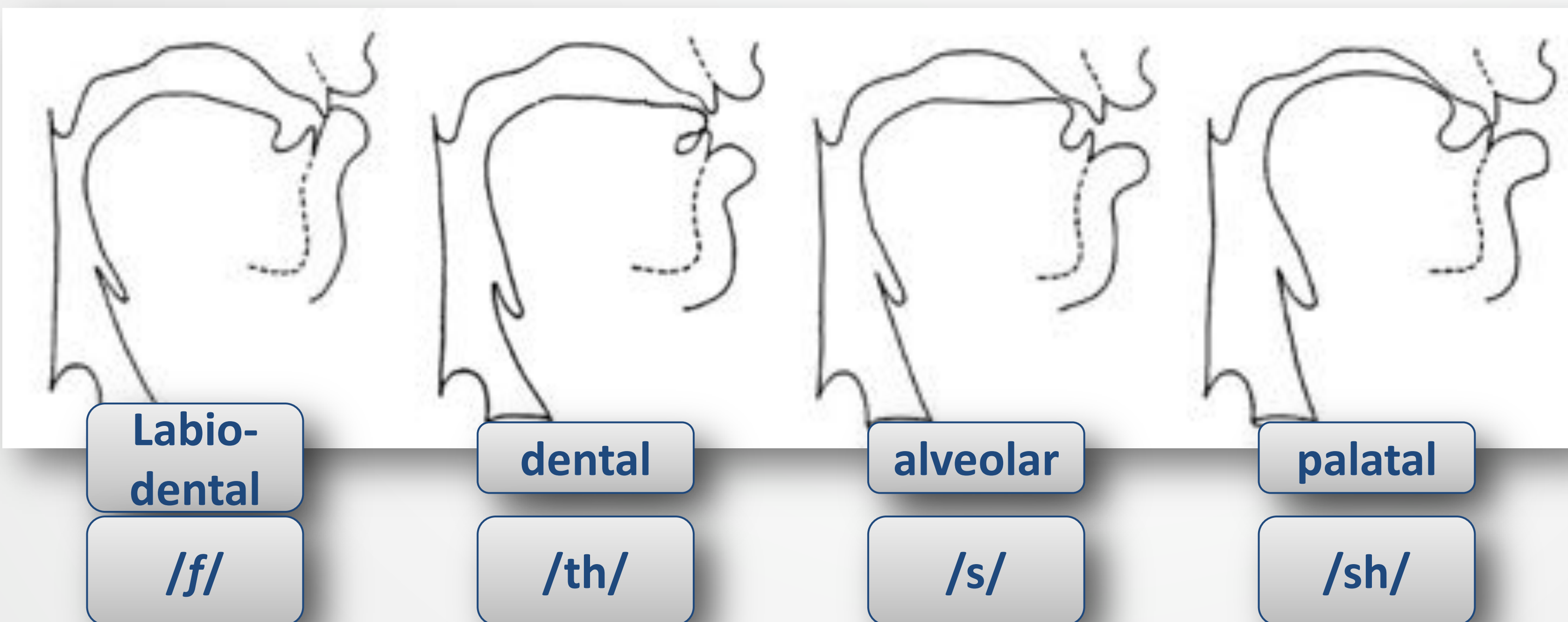
Fricatives (2/6)

- **Fricatives** are caused by acoustic turbulence at a **narrow constriction** whose position determines the sound.

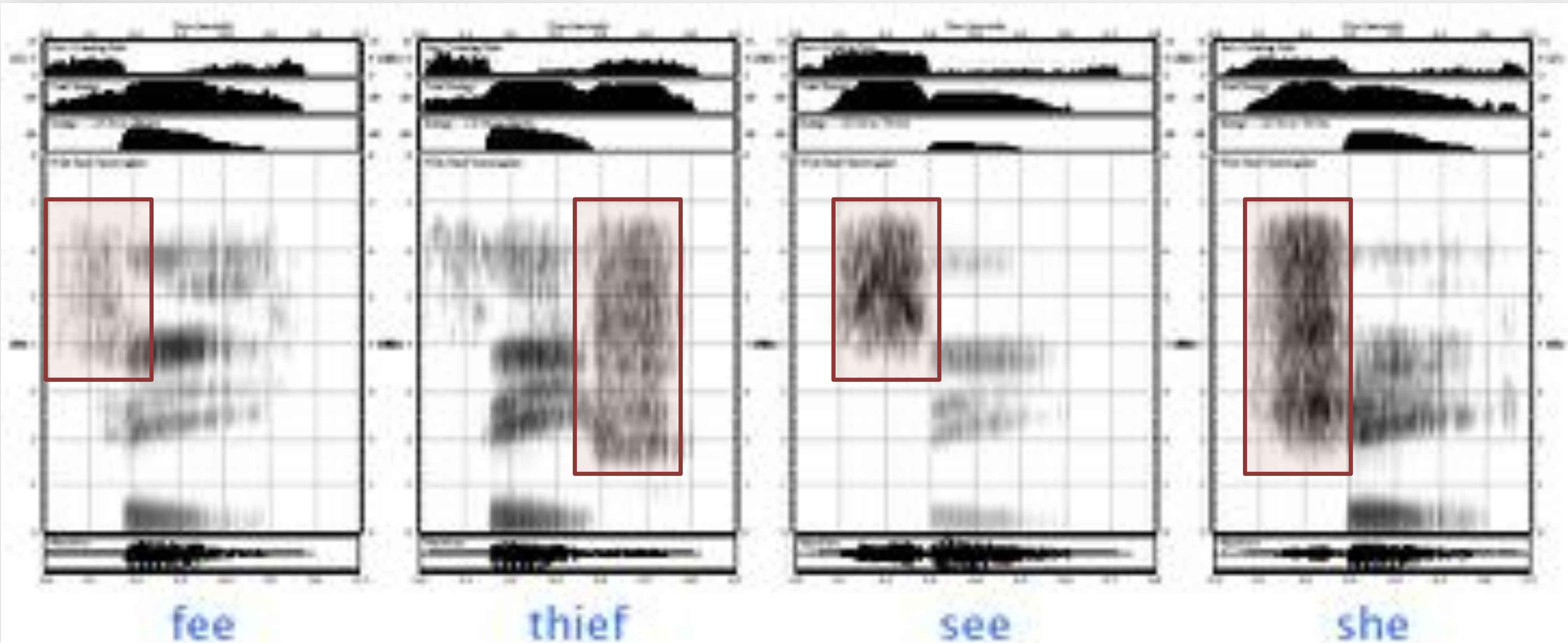


Fricatives

- **Fricatives** have four places of articulation.
- Each place of articulation has a **voiced** fricative (i.e., the glottis can be vibrating), and an **unvoiced** fricative.

	Unvoiced		Voiced	
Labio-dental	*/f/*	***f***ee	*/v/*	***V***endetta
Dental	*/th/*	***th***ief	*/dh/*	***Th***ee
Alveolar	*/s/*	***s***ee	*/z/*	***Z***ardo***z***
Palatal	*/sh/*	***sh***e	*/zh/*	***Zh***a-***zh***a

Unvoiced fricatives



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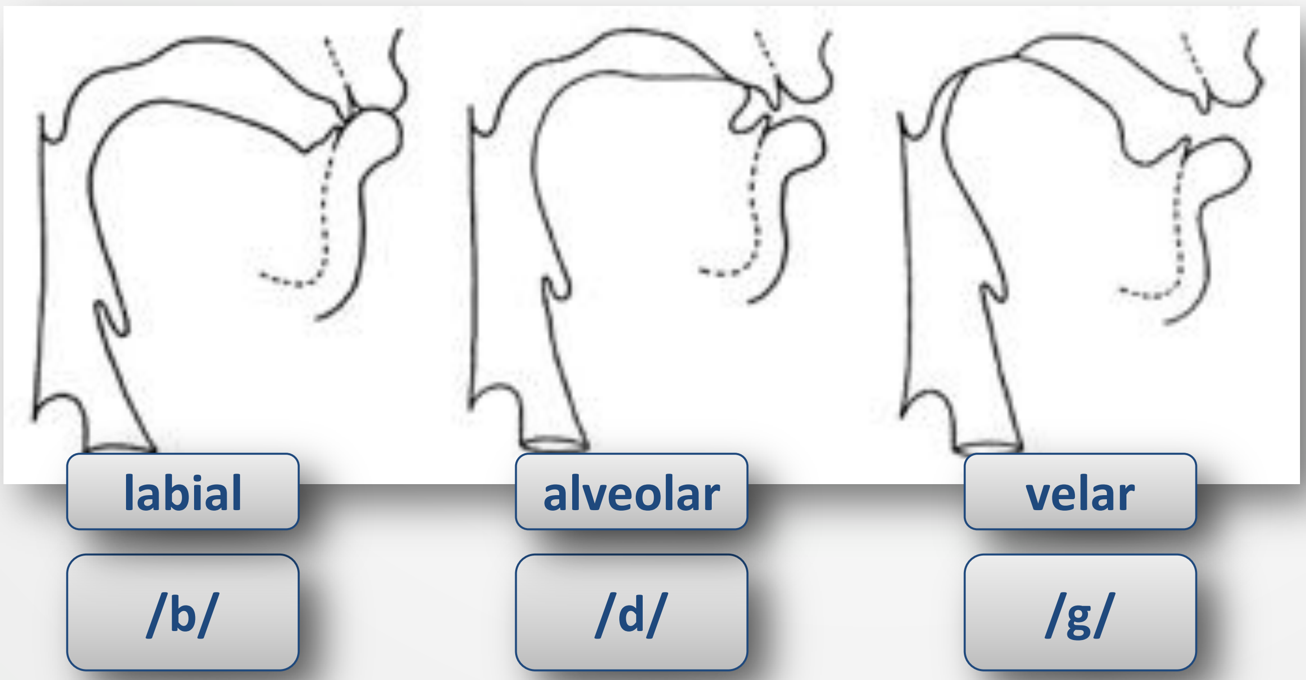
Plosives (3/6)

- **Plosives** build pressure behind a **complete closure** in the vocal tract.
- A **sudden release** of this constriction results in **brief noise**.



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Plosives

- **Plosives** have three places of articulation:

	Unvoiced		Voiced	
Labial	*/p/*	***p***or***p***oise	*/b/*	***b***a***b***oon
Alveolar	*/t/*	***t***or***t***	*/d/*	***d***o***d***o
Velar	*/k/*	***k***i***ck***	*/g/*	***G***oo***g***le

- **Voiced** stops are usually characterized by a "**voice bar**" during closure, indicating the vibrating glottis.
- Formant **transitions** are very **informative** in classification.

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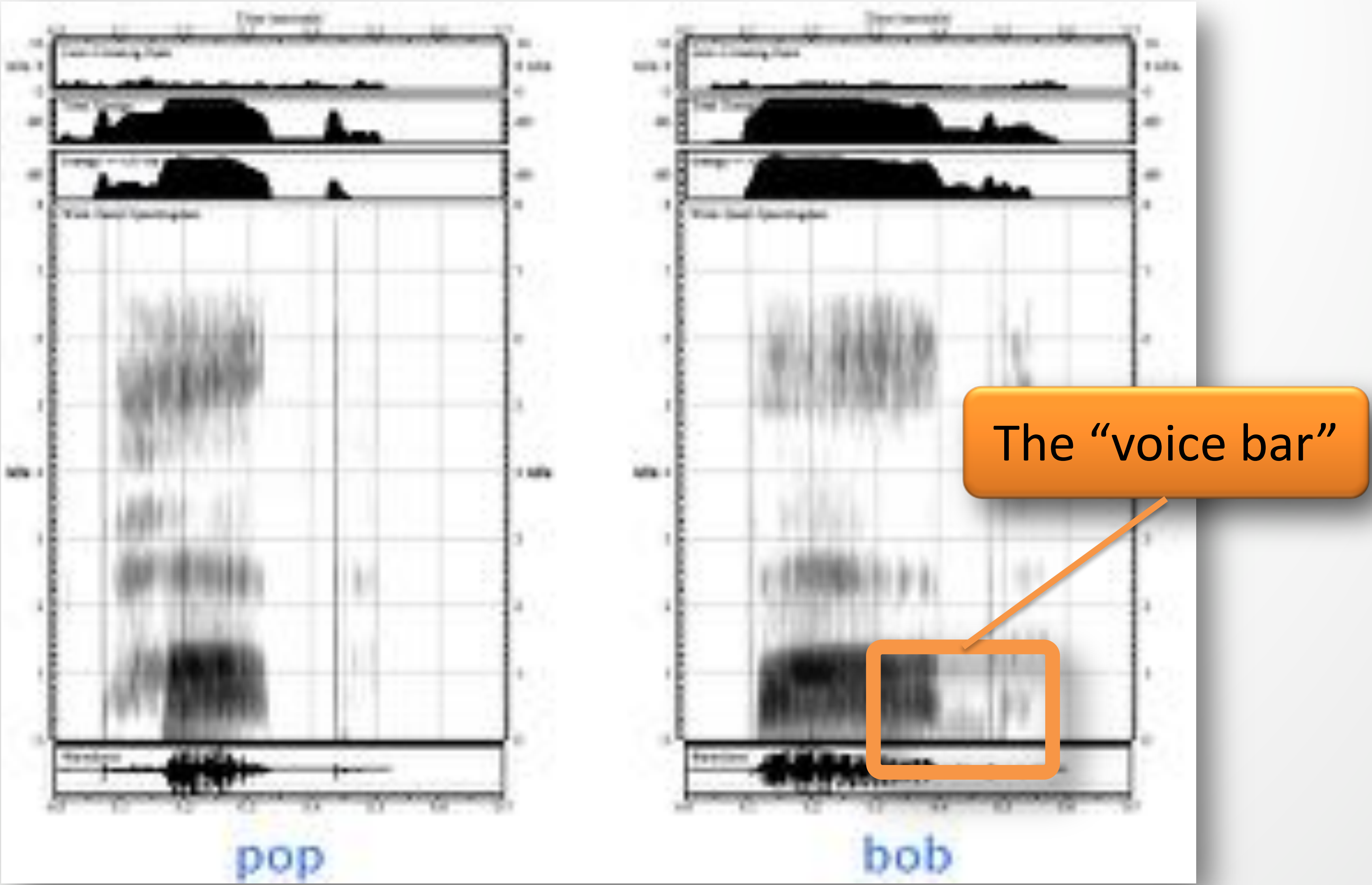
Voicing in plosives



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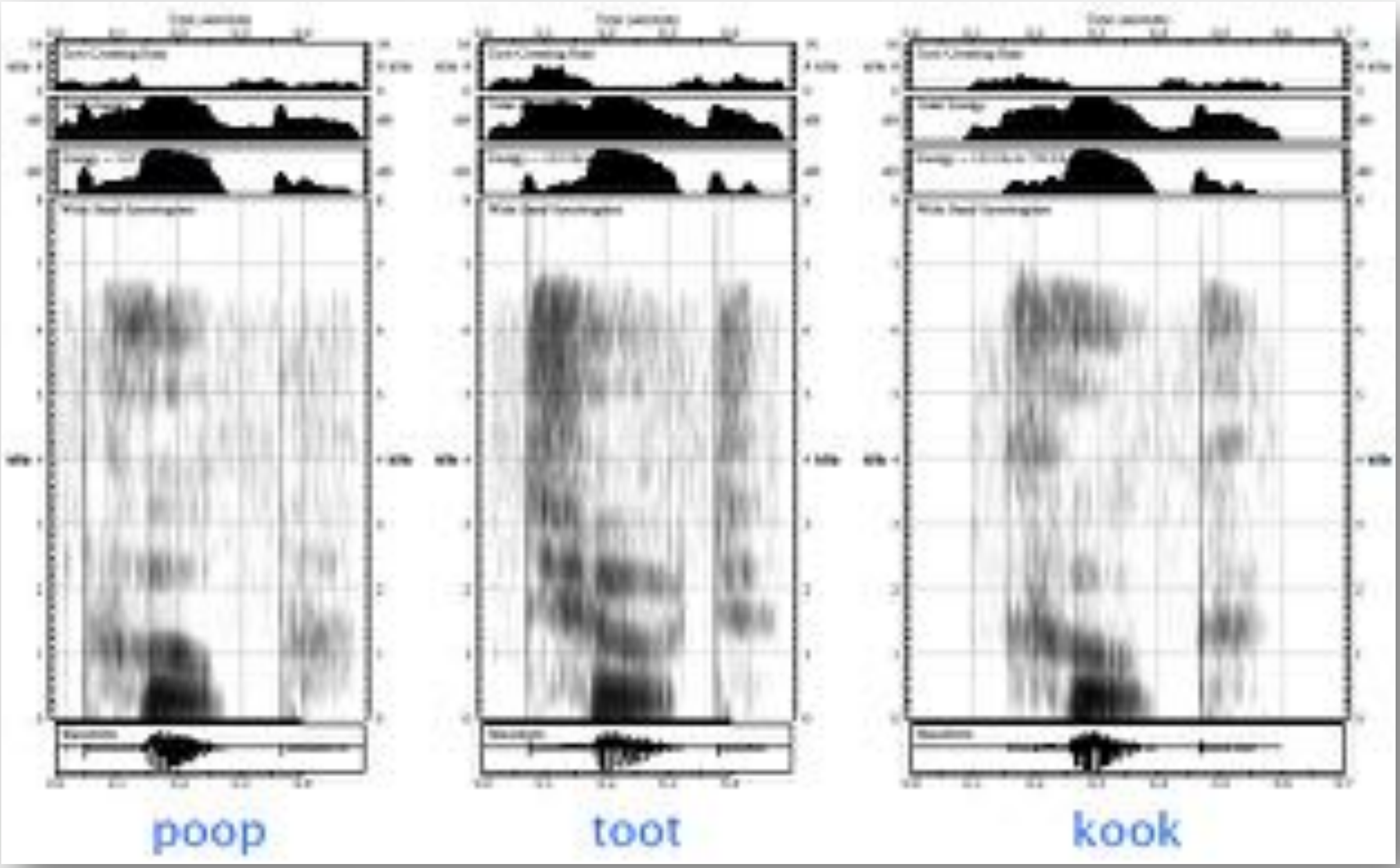
Formant transitions in plosives



- Despite a **common** vowel, the **motion** of F_2 and F_3 into (and out of) the vowel helps identify the plosive.

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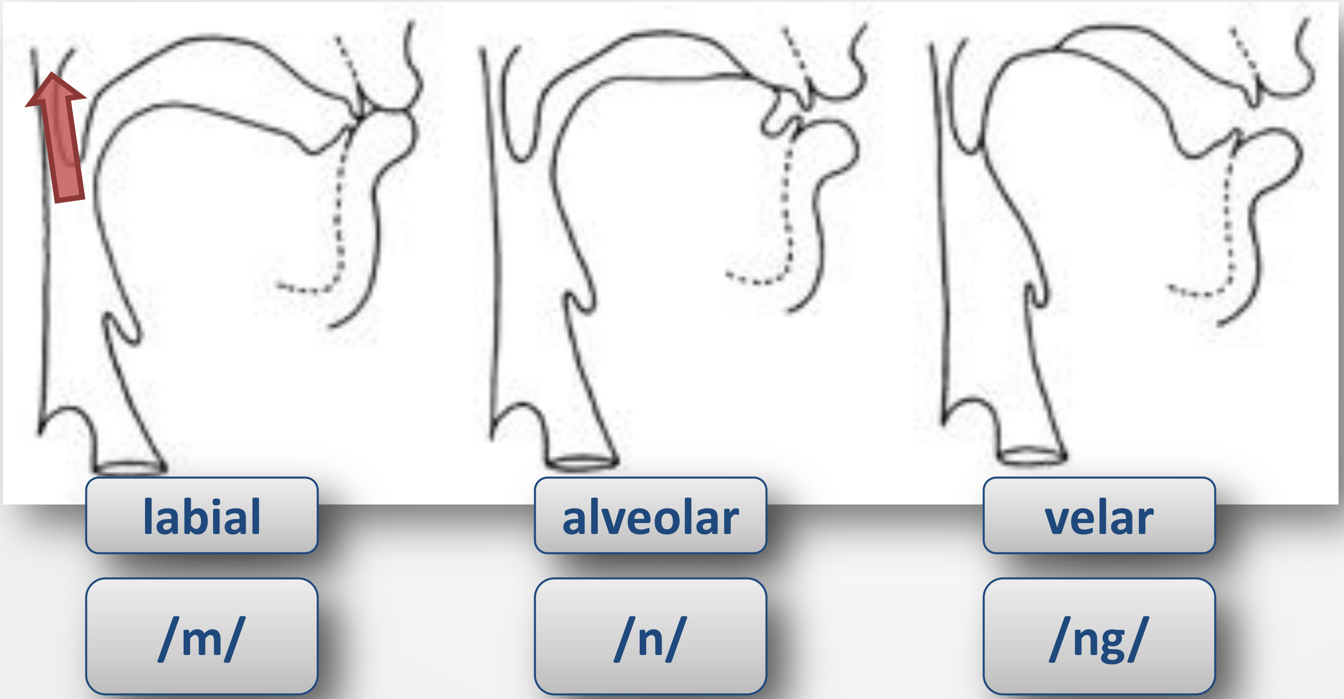
Nasals (4/6)

- **Nasals** involve lowering the velum so that air passes through the **nasal cavity**.
- **Closures** in the oral cavity (at same positions as plosives) change the resonant characteristics of the nasal sonorant.



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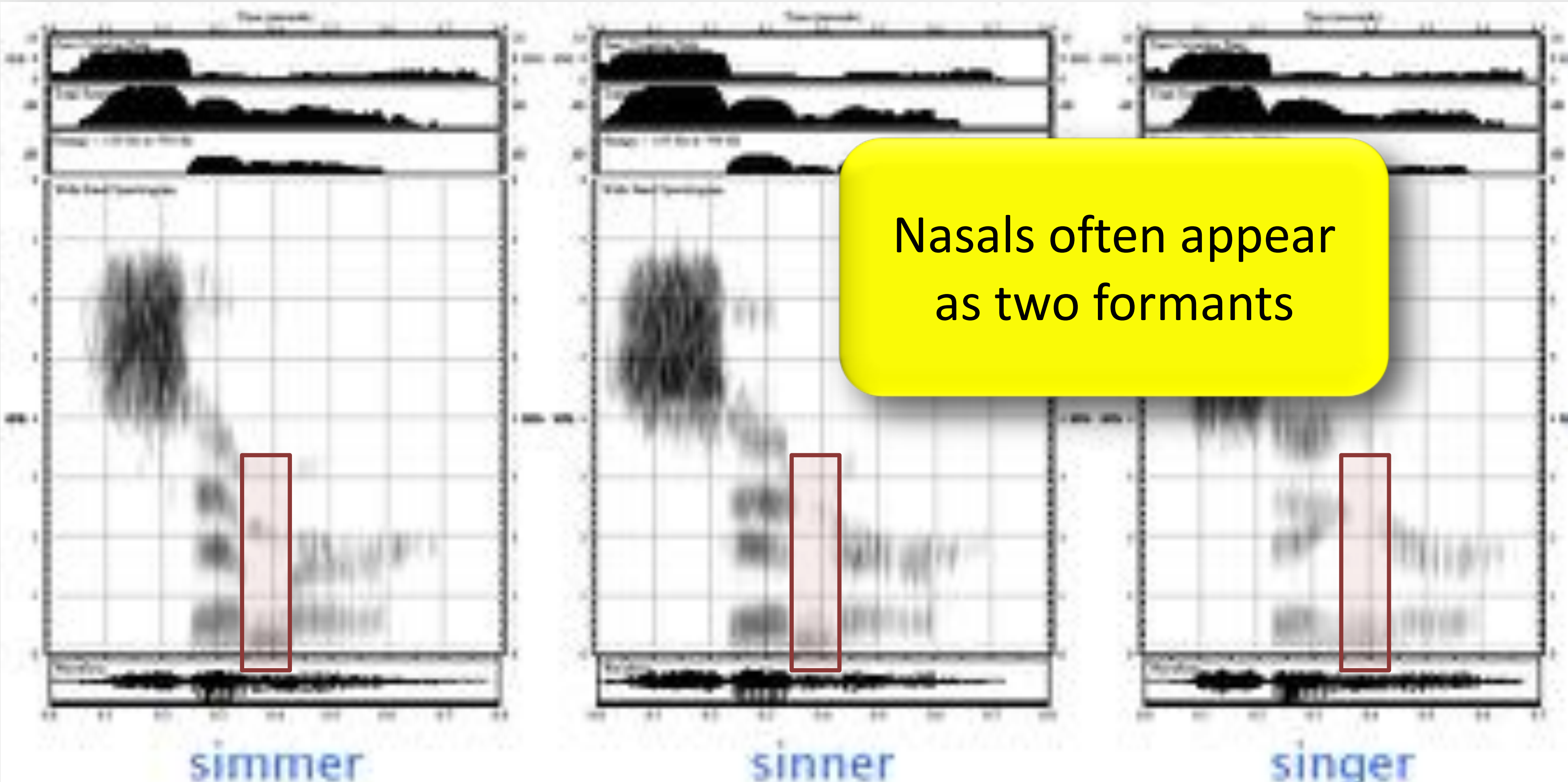
Formant transitions among nasals



Nasals often appear as two formants

- Despite a common vowel, the motion of F_2 and F_3 before and after each nasal helps to identify it.

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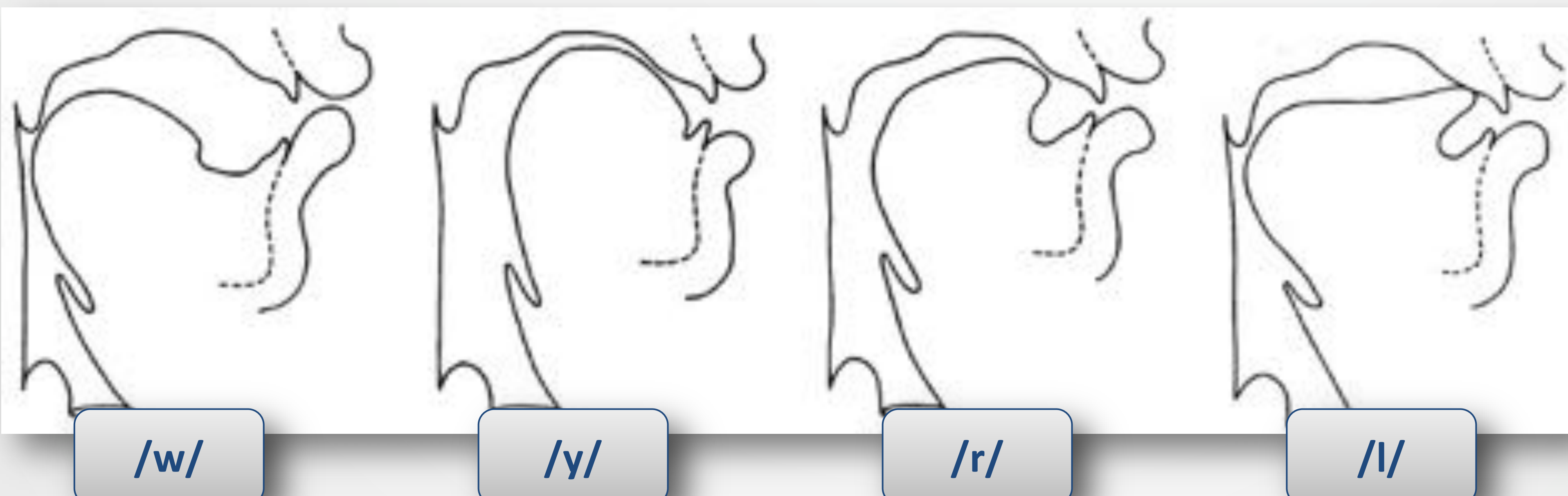
Semivowels (5/6)

- **Semivowels** act as consonants in syllables and involve constriction in the vocal tract, but there is **less turbulence**.
  - They also involve slower articulatory motion.
- **Laterals** involve airflow around the **sides** of the tongue.



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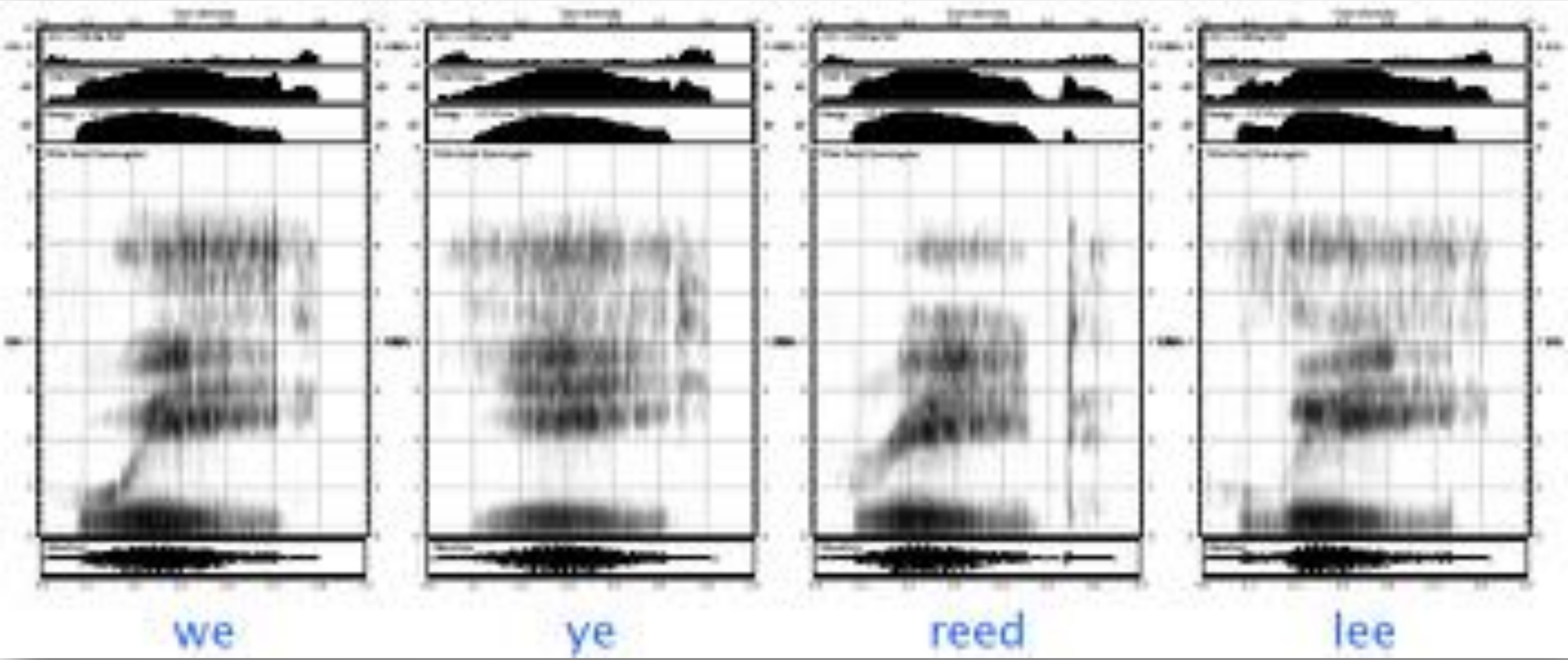
Semivowels

- Semivowels are often sub-classified as glides or liquids.

	Semivowel		Nearest vowel
Glides	/w/	Wow	/uw/
	/y/	yoyo	/iy/
Liquids	/r/	rear	/er/
	/l/	Lulu	/ow/

- Semivowels are more constricted versions of corresponding vowels.
  - Similar formants, though generally weaker.

Semivowels



- Note the drastic formant transitions which are more typical of semivowels.

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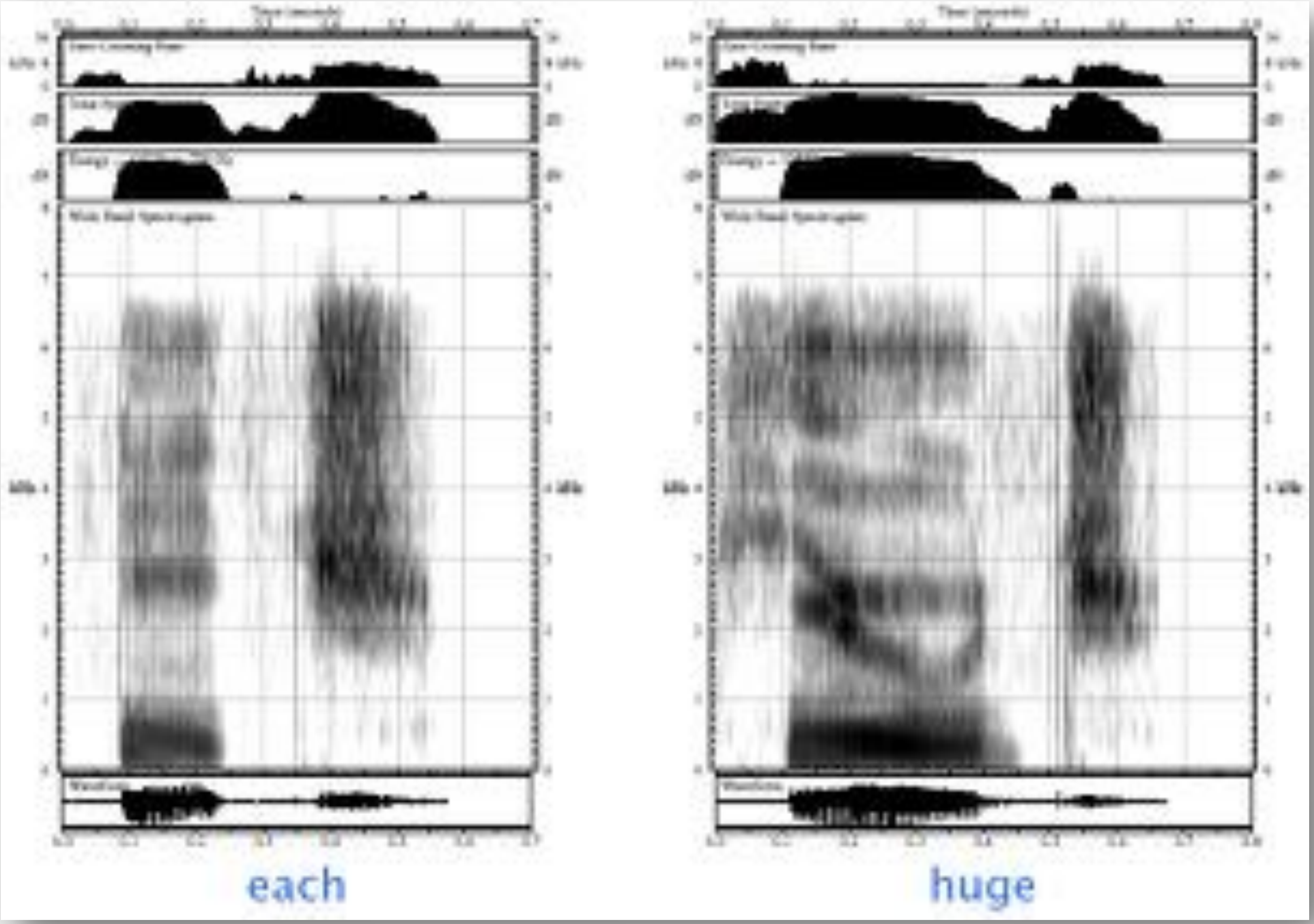
Affricates and aspirants (6/6)

- There are two **affricates**: /jh/ (voiced; e.g., ***j**u**dge***) and /ch/ (unvoiced; e.g., ***ch**ur**ch***).
  - These involve an **alveolar stop** followed by a **fricative**.
  - Voicing in /jh/ is normally indicated by voice bars, as with plosives.

- There's only one **aspirant** in Canadian English: /h/ (e.g., ***h**at*)
  - This involves turbulence generated at the **glottis**,
  - In Canadian English, there is **no** constriction in the vocal tract.

Affricates and aspirants



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Alternative pronunciations

- **Pronunciations** of words can vary significantly, but with observable **frequencies**.
  - The **Switchboard** corpus is a phonetically annotated database of speech recorded in telephone conversations.

because				about			
ARPAbet	%	ARPAbet	%	ARPAbet	%	ARPAbet	%
b iy k ah z	27%	k s	2%	ax b aw	32%	b ae	3%
b ix k ah z	14%	k ix z	2%	ax b aw t	16%	b aw t	3%
k ah z	7%	k ih z	2%	b aw	9%	ax b aw dx	3%
k ax z	5%	b iy k ah zh	2%	ix b aw	8%	ax b ae	3%
b ix k ax z	4%	b iy k ah s	2%	ix b aw t	5%	b aa	3%
b ih k ah z	3%	b iy k ah	2%	ix b ae	4%	b ae dx	3%
b ax k ah z	3%	b iy k aa z	2%	ax b ae dx	3%	ix b aw dx	2%
k uh z	2%	ax z	2%	b aw dx	3%	ix b aa t	2%

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Known effects of pronunciation

- Speakers tend to **drop** or **change** pronunciations in **predictable** ways in order to reduce the effort required to **co-ordinate** the various articulators.
  - **Palatalization** generally refers to a **conflation** of phonemes closer to the frontal palate than they 'should' be.
  - **Final t/d deletion** is simply the **omission** of alveolar plosives from the ends of words.

Palatalization			Final t/d Deletion		
Phrase	**Lexical**	**Reduced**	**Phrase**	**Lexical**	**Reduced**
set your	s eh t y ow r	s eh ch er	find him	f ay n d h ih m	f ay n ix m
not yet	n aa t y eh t	n aa ch eh t	and we	ae n d w iy	eh n w iy
did you	d ih d y uw	d ih jh y ah	draft the	d r ae f t dh iy	d r ae f dh iy

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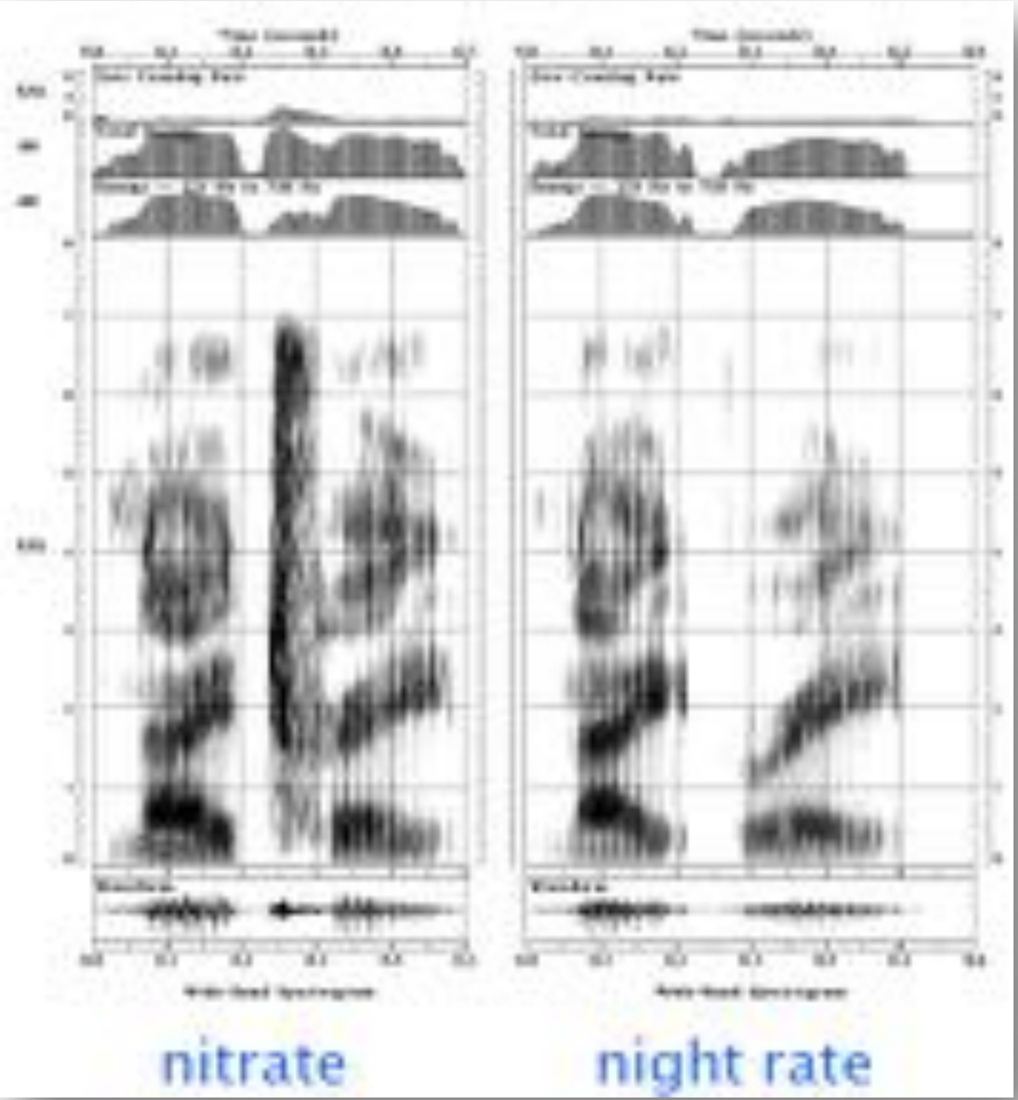
Variation at syllable boundaries



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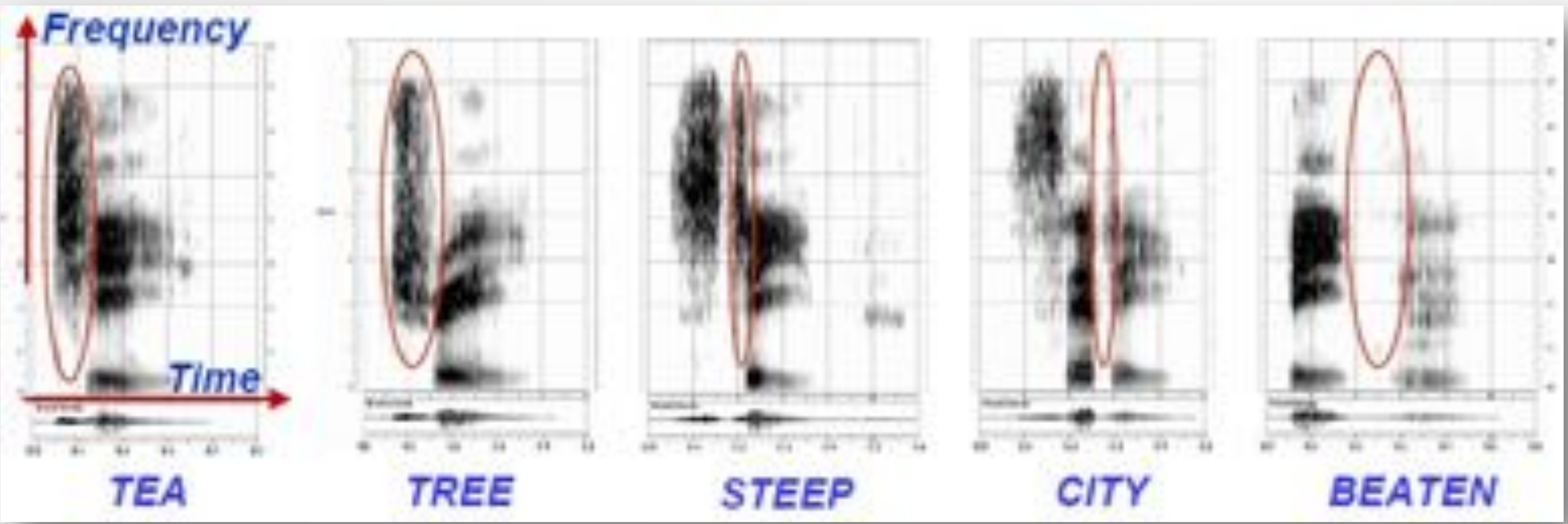
Phonological variation

- The acoustics of a phoneme depend strongly on the **context** in which that phoneme occurs.



*That must make **recognizing** phonemes hard, right?*
How do humans do it?

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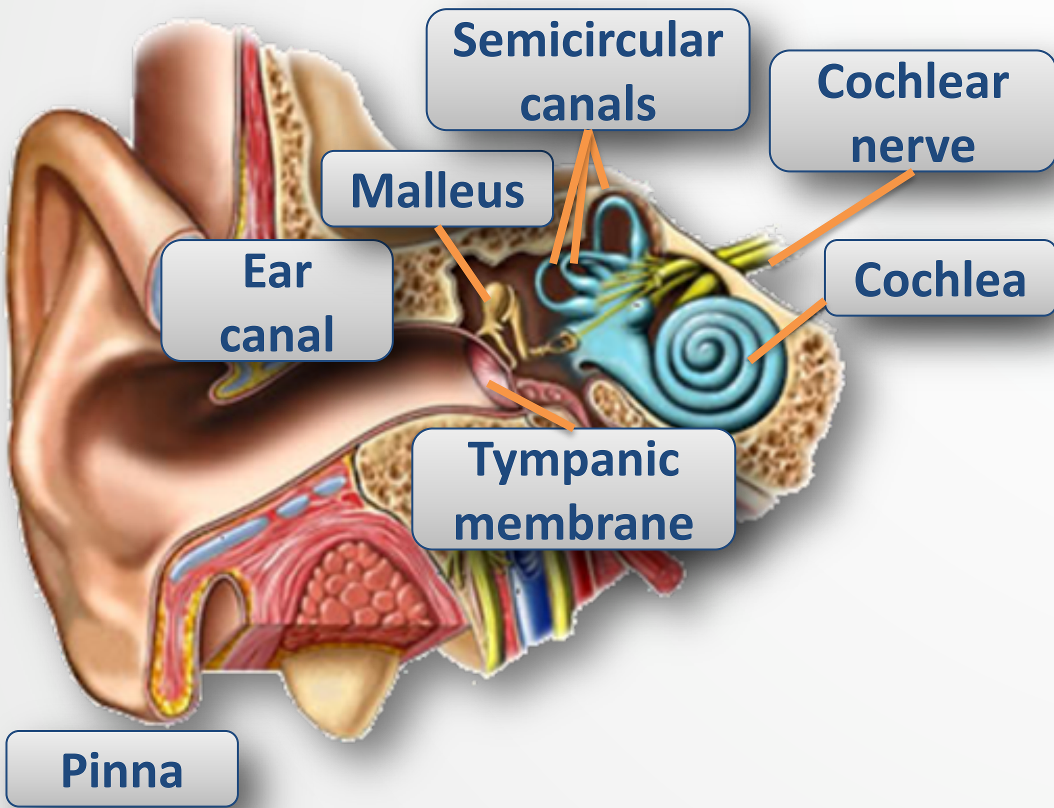
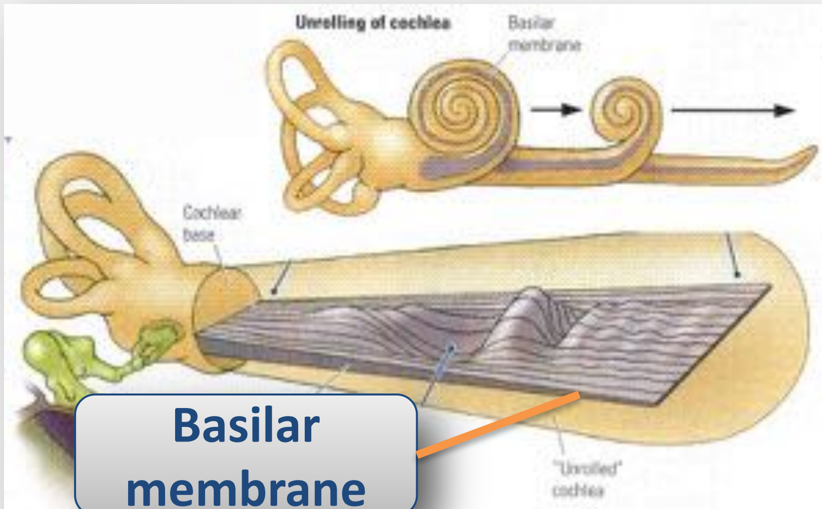
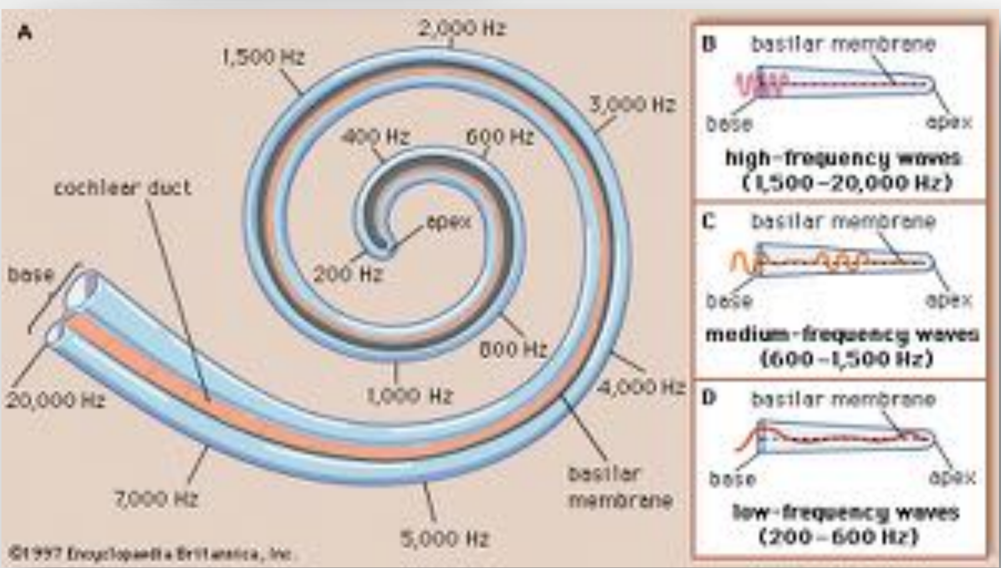
The inner ear



- Time-variant waves enter the ear, vibrating the **tympanic membrane**.
- This membrane causes tiny bones (incl. **malleus**) to vibrate.
- These bones in turn vibrate a structure within a shell-shaped bony structure called the **cochlea**.

The cochlea and basilar membrane





- The **basilar membrane** is covered with tiny hair-like nerves – some near the **base**, some near the **apex**.
- **High** frequencies are picked up near the base, **low** frequencies near the apex.
- These nerves fire when activated, and communicate to the brain.

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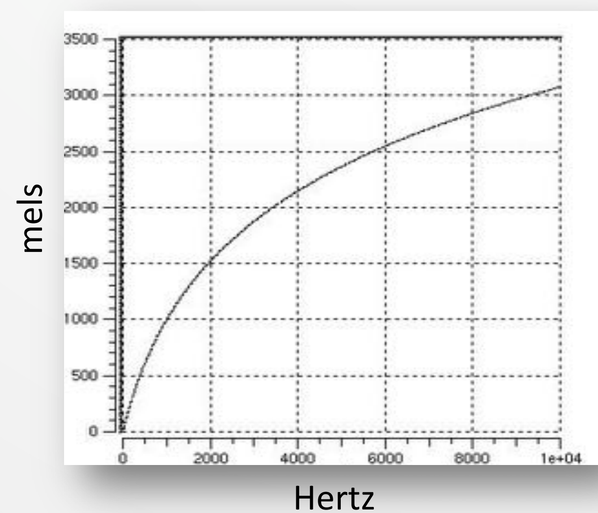
The Mel-scale

- Human hearing is **not** equally sensitive to **all** frequencies.
  - We are **less** sensitive to frequencies > 1 kHz.

- A **mel** is a unit of pitch. Pairs of sounds which are **perceptually** equidistant in pitch are separated by an equal number of **mels**.

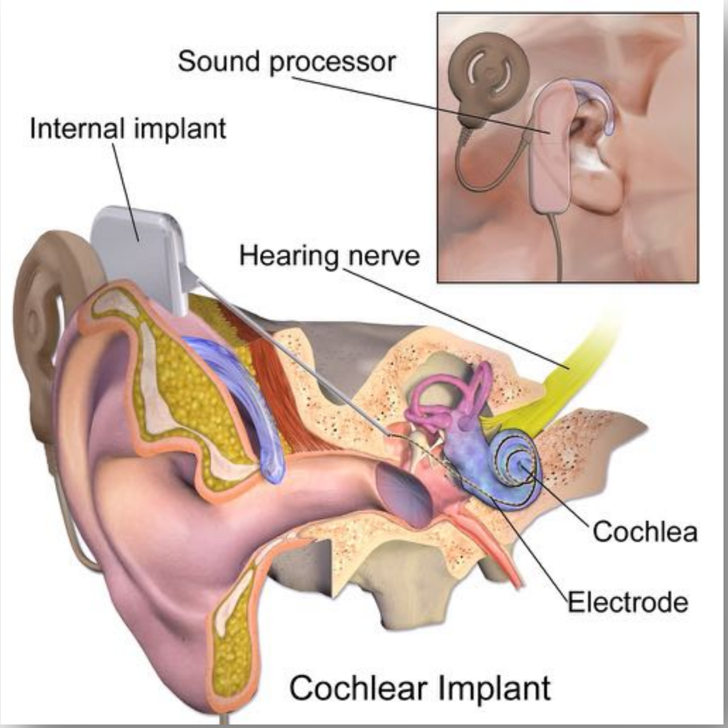
$$Mel(f) = 2595 \log_{10}\left(1 + \frac{f}{700}\right)$$

(No need to memorize this either)



Aside – Challenges of perception

- **Cochlear implants** replace the basilar membrane and stimulate the auditory nerve directly.



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Next…

- How the Mel scale is used in ASR.
- Automatic speech recognition.