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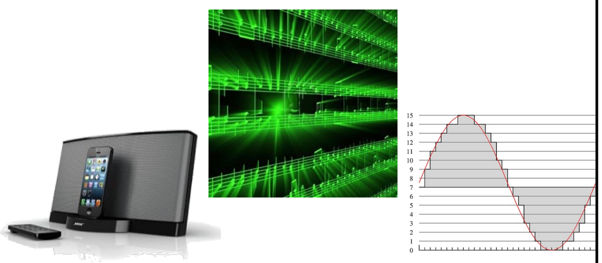


Lecture #08 – Psychoacoustics

ESE 1500 – Digital Audio Basics

1

Teaser – Dog Whistle

- What is special about a dog whistle?
  - https://www.youtube.com/watch?v=dk0HsvQ7m_E

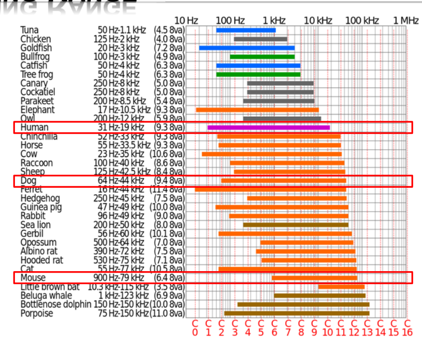
2

Teaser – Rodent Deterent

- How do these work?
- https://www.amazon.com/Ultrasonic-Repelling-Electronic-Repellent-Squirrels/dp/B081F5WL6W/ref=sr_1_20?dchild=1&keywords=ultrasonic+rodent+repeller&qid=1613513635&sr=8-20

3

Hearing Range



https://commons.wikimedia.org/wiki/File:Animal_hearing_frequency_range.svg

4

Observe

- There are sounds we cannot hear
  - Depends on frequency

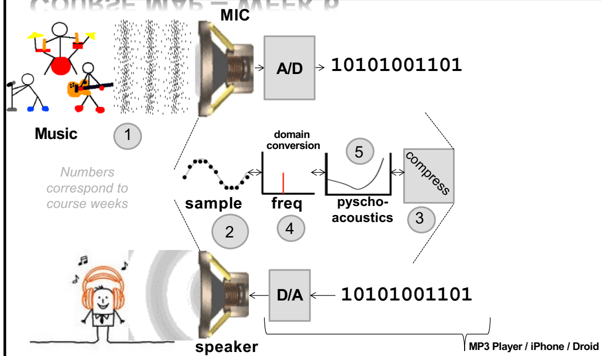
5

Lecture Topics

- **Part 1**
  - Motivation: hearing range
  - Where are we on course map?
  - Psychoacoustics: basics
    - Structure of Human Ear / encoding signals to brain
- **Part 2: psychoacoustics model and implications**
  - Engineering Model
  - Human Hearing Limits
  - Critical Bands (Frequency bins)
  - Next Lab
- **References**

6

Course Map – Week 6



7

Psychoacoustics

9

What is Psychoacoustics?

- **Scientific study of sound perception**
  - Branch of science studying the psychological and physiological responses associated with sound
  - Also, considered a branch of: psychophysics
  - Human physical (and neurological) mechanism for sound perception
- **Why study sound & human perception?**
  - Example: FREQUENCY vs. PITCH
    - Frequency of sound: "how often" air particles vibrate (Hz)
    - Pitch of sound: the sensation of frequency
      - How our brains "interpret" the frequency of a sound
- **Things may "sound" one way…**
  - …but be interpreted by our brains very differently!

10

Psychoacoustics & Digital Music

- **How does psychoacoustics relate to MP3?**
- **The "consumer" of an MP3 is the human ear…**
  - Knowing more about brain's interpretation of sound…
  - …helps us remove things human's can't hear anyway
- **We've used some of this in our system already:**
  - Limit of human perception of sound: 20 Hz to 20,000 Hz
    - We put an anti-aliasing filter limiting incoming audio
  - Fixes our sampling rate, less data to store as a result!

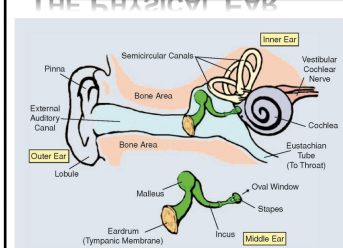
11

Our study of Psychoacoustics

- **Structure of Human Ear / encoding signals to brain**
- **Human Hearing Limits**
- **Critical Bands**
- **Frequency Bins**
- **Masking (Spatial vs. Temporal) [two week]**
- **Applied Psychoacoustics [following week]**
  - Using all of the above to build...the "Psychoacoustical Model"
  - Perceptual Coding in MP3 (using the model to compress MP3s)

12

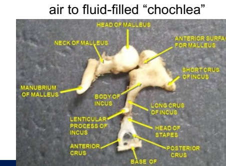
The Physical Ear



[FIG2] The cross section view of the ear displaying the components of the outer, the middle, and the inner ear.

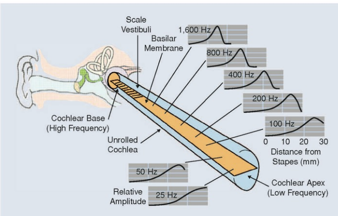
Converts vibrations in air (sound) into mechanical motion in the middle-ear!

- **Outer Ear**
  - Guides sound waves into 'auditory canal'
- **Middle Ear**
  - Ear Drum – transmits sound from air to 3 bones in inner ear: ossicles (*hammer, anvil, stirrup*)
- **Inner Ear**
  - Ossicles – transmit sound from air to fluid-filled "chochlea"



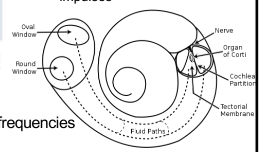
13

The Physical Ear – "Cochlea"



[FIG3] An illustration of an uncoiled cochlea. Due to the greater stiffness and smaller mass, the base of the basilar membrane is tuned to high frequencies while the apex resonates best with the low frequencies. The amplitude of the traveling waves across the membrane shows the frequency-to-place mapping.

- **Cochlea – "snail shell"**
  - Fluid-filled "labyrinth"
  - Located in: "inner-ear"
  - Spiral Shaped (snail shell)
  - Hair inside cochlea 'resonates' according to incoming vibrations in the liquid
    - Stereovilli (name of hair)
  - Hairs convert vibration into nerve impulses



Picture above – uncoiled cochlea…
-- different stereovilli (Hairs) resonate at different frequencies
-- our ear sense in Frequency Domain!

http://www.youtube.com/watch?v=zeo4qTnYOow

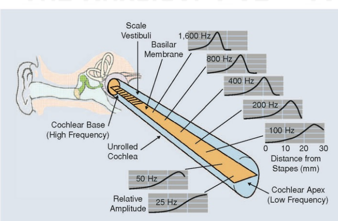
14

Cochlea Animation

- **https://www.youtube.com/watch?v=dyenMluFaUw**

15

The Physical Ear – Take-Away



[FIG3] An illustration of an uncoiled cochlea. Due to the greater stiffness and smaller mass, the base of the basilar membrane is tuned to high frequencies while the apex resonates best with the low frequencies. The amplitude of the traveling waves across the membrane shows the frequency-to-place mapping.

- **Cochlea**
  - directly senses frequencies
  - Captures frequency domain
  - …not time domain
- **Frequency sensitive locations**
  - activated by sound waves
- **Neurons sense activation**

Picture above – uncoiled cochlea…
-- different stereovilli (Hairs) resonate at different frequencies
-- our ear performs Fourier Transform!

16

Take-Away

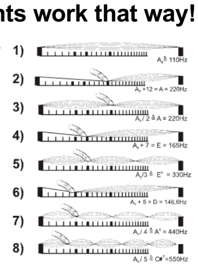
- **Our ear works in the frequency domain.**
- **We could consider devices that**
  - Directly recorded frequencies
    - Collection of resonators?
  - Directly produced frequencies
    - Collection of vibrators
      - Tuning forks
      - Strings
      - Pipes
      - …sound familiar?

17

Direct Frequency Generation

- **All traditional musical instruments work that way!**
  - Piano, guitar, violin – vibrating strings

Feliciano Guimarães from Guimarães, Portugal / CC BY (https://creativecommons.org/licenses/by/2.0)



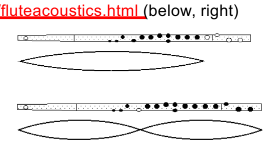
By user:Mjchael - made by me (Corel-Draw), CC BY-SA 2.5, https://commons.wikimedia.org/w/index.php?curid=1251597

More: Lhttps://www.zmescience.com/science/physics/guitar-strings-vibrate/

18

Direct Frequency Generation

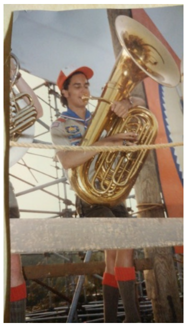
- **All traditional musical instruments work that way!**
  - Piano, guitar, violin – vibrating strings
  - Flute, trumpet, pipe organ – pipes
    - http://newt.phys.unsw.edu.au/jw/woodwind.html
    - http://newt.phys.unsw.edu.au/jw/fluteacoustics.html (below, right)

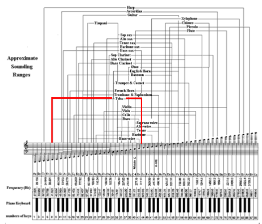


By Photo by Yasuhiko Sano, Nov 2005 - http://homepage2.nifty.com/iwatake/, Public Domain, https://commons.wikimedia.org/w/index.php?curid=435915

19

Time Domain Advantage?



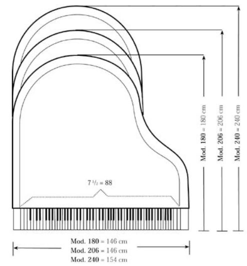


Larry Solomn:
http://solomonsmusic.net/insrange.htm

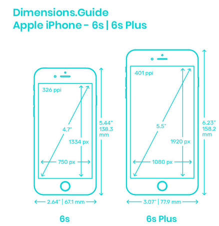
20

Time Domain Advantage?

1.5m x 2.4m



0.07m x 0.14m



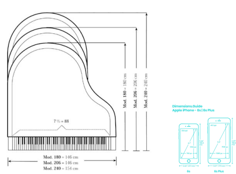
http://www.bluebookofpianos.com/types.html

https://www.dimensions.guide/element/apple-iphone-6s-6s-plus

21

Time Domain Advantage?

- **Can produce (receive) many frequencies**
  - Without large number of strings (vibrators, pipes)
  - Without large footprint for strings and resonant cavities
- **Smaller/cheaper**
  - Exploiting cheap processing from Moore's Law



http://www.bluebookofpianos.com/types.html

https://www.dimensions.guide/element/apple-iphone-6s-6s-plus

22

Penn Engineering

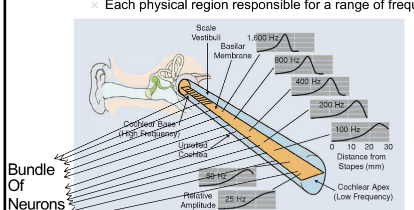
ESE 1500 - Spring 2023 DeHon

Part 2

23

Physical Ear to Engineering Model

- **With knowledge of structure/function of ear:**
  - We can model cochlea's behavior as bank of filters / bandpass filters
    - Cochlea breaks down auditory input into frequency ranges
    - Sends different frequencies down different nerve pathways!
    - Each physical region responsible for a range of frequencies.



Each Frequency encoded independently on the auditory nerve

Brain ultimately "interprets" these Encoded signals as sound

24

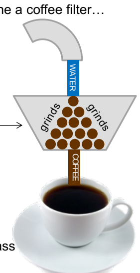
Recall -- Day 5 -- filter

We know how to avoid aliasing…

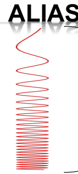
- **What is a filter you ask?**
  - Imagine a coffee filter…

Water, Ground coffee beans go into Filter…

Coffee Filter →



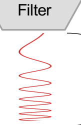
Only delicious coffee passes through filter… "grinds" cannot pass



Signals ranging in frequencies from 20Hz to 40kHz (100KHz, …) go into filter

Electronic Filter

Called a "low pass" filter
Has a "cutoff" frequency of 20 kHz



Only "delicious" signals ranging from 20Hz to 20kHz pass through filter (aka Audio Signals)

25

Filters

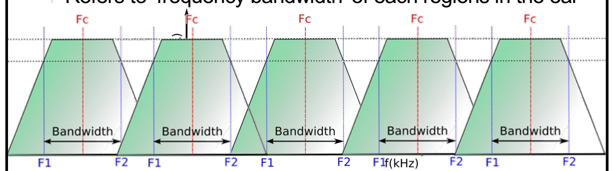
- **For anti-aliasing saw low-pass filter**
  - Only allow low frequencies to pass through
- **General, can develop filters that select a range of signals**
- **Band-pass filter**
  - Only allow frequencies in a "band"
  - Between some low cutoff frequency and high cutoff

26

26

Physical Ear – Limits of Human Perception

- **Critical Frequency Bands**
  - Refers to 'frequency bandwidth' of each regions in the ear



- A 'sharply tuned' filter has good frequency resolution
  - Allows frequencies in band pass well, but not others
  - Brain can then 'resolve' different frequencies

27

27

Critical Frequency Bands – How Many?

- **"Bark" scale –**
  - Maps frequency intervals into their respective critical band number

Number	Center Freq. (Hz)	Cut-off Freq. (Hz)	Bandwidth (Hz)	Number	Center Freq. (Hz)	Cut-off Freq. (Hz)	Bandwidth (Hz)
		20		13	1850	2000	280
1	50	100	80	14	2150	2320	320
2	150	200	100	15	2500	2700	380
3	250	300	100	16	2900	3150	450
4	350	400	100	17	3400	3700	550
5	450	510	110	18	4000	4400	700
6	570	630	120	19	4800	5300	900
7	700	770	140	20	5800	6400	1100
8	840	920	150	21	7000	7700	1300
9	1000	1080	160	22	8500	9500	1800
10	1170	1270	190	23	10500	12000	2500
11	1370	1480	210	24	13500	15500	3500
12	1600	1720	240				

28

28

Critical Frequency Bands – How Many?

- **"Bark" scale –**
  - Maps frequency intervals into their respective critical band number
  - 24 frequency bins (or "barks"), get wider as frequency increases!

Number	Center Freq. (Hz)	Cut-off Freq. (Hz)	Bandwidth (Hz)	Number	Center Freq. (Hz)	Cut-off Freq. (Hz)	Bandwidth (Hz)
		20		13	1850	2000	280
1	50	100	80	14	2150	2320	320
2	150	200	100	15	2500	2700	380
3	250	300	100	16	2900	3150	450
4	350	400	100	17	3400	3700	550
5	450	510	110	18	4000	4400	700
6	570	630	120	19	4800	5300	900
7	700	770	140	20	5800	6400	1100
8	840	920	150	21	7000	7700	1300
9	1000	1080	160	22	8500	9500	1800
10	1170	1270	190	23	10500	12000	2500
11	1370	1480	210	24	13500	15500	3500
12	1600	1720	240				

29

29

OK, now…some tests…

- **How well can you hear? (range)**
  - 20 Hz to 20kHz – frequency increasing over 20 seconds
  - Can you hear tone the entire time, or do is it appear to go silent at some point?
  - Tells you how high (and maybe how low) of frequencies you can hear
    - Probably need to switch to audacity on laptop to see when still playing…
    - (or mouse over sound to see playbar)

30

30

OK, now…some tests…

- **Can you hear two frequencies at once? (selectivity)**
  - Let's try: 400 Hz and 1000 Hz
  - First independent references
  - Then together

31

31

Different Bands

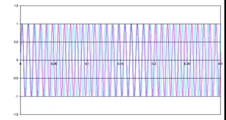
- **Bands**
  - 400Hz
  - 1000Hz

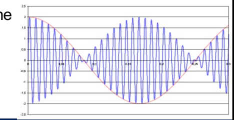
Number	Center Freq. (Hz)	Cut-off Freq. (Hz)	Bandwidth (Hz)
		20	
1	50	100	80
2	150	200	100
3	250	300	100
4	350	400	100
5	450	510	110
6	570	630	120
7	700	770	140
8	840	920	150
9	1000	1080	160
10	1170	1270	190
11	1370	1480	210
12	1600	1720	240

Number	Center Freq. (Hz)	Cut-off Freq. (Hz)	Bandwidth (Hz)
13	1850	2000	280
14	2150	2320	320
15	2500	2700	380
16	2900	3150	450
17	3400	3700	550
18	4000	4400	700
19	4800	5300	900
20	5800	6400	1100
21	7000	7700	1300
22	8500	9500	1800
23	10500	12000	2500
24	13500	15500	3500

OK, now…some tests…

- **Frequency Resolution…(bands)**
  - In 1000 Hz to 2000 Hz octave…
    - Brain can't perceive changes in frequency
    - smaller than 3.6 Hz
  - Plays 1500Hz tone then 1502Hz
    - Aside from maybe a click in the middle, can you tell difference between tones?
    - Keep same tones, but add a 1500Hz tone on second track playing whole time.
    - Now hear interference demonstrating that first track did change tones.

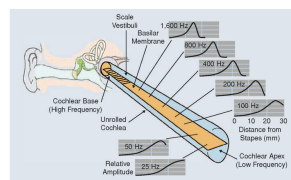




Frequency Quantization

- **Frequency Resolution…(bands)**
  - In 1000 Hz to 2000 Hz octave…
    - Brain can't perceive changes in frequency
    - smaller than 3.6 Hz
- **What does this tell us about frequency quantization?**

Physical Ear to Engineering Model



- **Limits of Human Hearing…easy to see from Cochlea**
  - Cochlea only so long…
    - lowest frequencies: 20 Hz
    - Highest frequencies: 20 kHz
- **Also helps us understand 'selectivity'**
  - Our brain can choose to 'listen' to output of various filters
  - *Example: At a party, but you can concentrate on conversation!*

Sound Intensity & Loudness

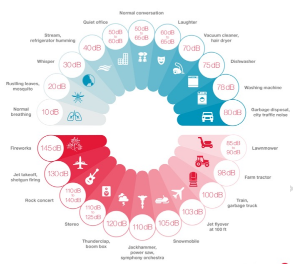
Sound Intensity – "Loudness"

- **But first, we must discuss: deci-*Bels* (dB)**
  - Logarithmic unit in engineering: compare levels (fractions)
  - Compare two physical quantities: power, intensity, etc
  - Often compare quantity to a reference value
- **Sound and (dB)**
  - Sound is compression/expansion of air
  - We use (dB) to compare two air pressures in acoustics:
    - Lowest limit of human ear sensitivity: 20 μPascals (μPa)
      - We compare all sounds to this lower limit (reference sound pres.)

Loudness-Sound Pressure Level (L_{SPL}) = $20 * log_{10}\left(\frac{Sound\ pressure}{Reference\ Sound\ pressure}\right)$ in **dB**

Sound Intensity in (dB) – "Loudness"

How loud is too loud?



- Preclass 2:

Pressure (Pa)	Intensity (dB)
$2x10^{-5}$	
$2x10^{-4}$	
$2x10^{2}$	

- Preclass 3: Ratio of pressure between 20dB and 140dB?

38

38

Sound Intensity in (dB) – "Loudness"

Decibels SPL	Example Sound
140 dB	Pain
130 dB	
120 dB	Discomfort
110 dB	Jack hammers and rock concerts
100 dB	
90 dB	OSHA limit for industrial noise
80 dB	
70 dB	
60 dB	Normal conversation
50 dB	
40 dB	Weakest audible at 100 Hz
30 dB	
20 dB	Weakest audible at 10 kHz
10 dB	
0 dB	Weakest audible at 3 kHz
-10 dB	
-20 dB	

- **If sound intensity level is:**
- **140 dB** **20 dB**

$20log\left(\frac{P2}{P0}\right) = 140dB$ $20log\left(\frac{P1}{P0}\right) = 20dB$

- **Divide both sides by 20:**

$log\left(\frac{P2}{P0}\right) = 7$ $log\left(\frac{P1}{P0}\right) = 1$

$\frac{P2}{P0} = 10^7$ $\frac{P1}{P0} = 10^1$

$\frac{P2}{P1} = 1,000,000$

- **Sound with intensity of 140dB:**
  - *has a sound pressure 1 million times greater than the quietist sound we can hear (which is 20 uPa) -- OUCH!*

39

39

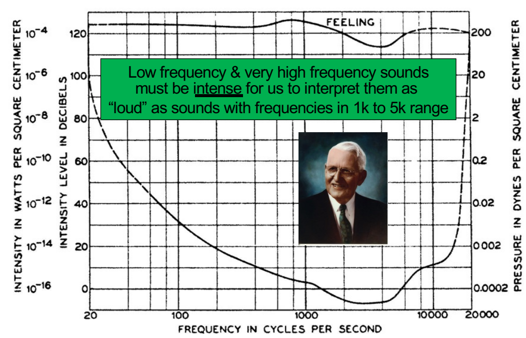
Sound Intensity in (dB) – "Loudness"

- **Loudness –**
  - subjective perception of intensity of sound
- **Intensity –**
  - Sound power per unit area
- **Does loudness change with frequency?**
  - Yes! Scientist: Harvey Fletcher (1940)
    - Measured loudness vs. frequency (Auditory Thresholds)
    - Same 'amplitude' sound can sound very quiet or really loud
      - All depends on its frequency
  - Turns out…
    - We are very sensitive to frequencies from 1kHz to 5kHz
      - They don't have to be 'intense' for us to hear them…why??

40

40

Auditory Thresholds – Measured by Fletcher



41

41

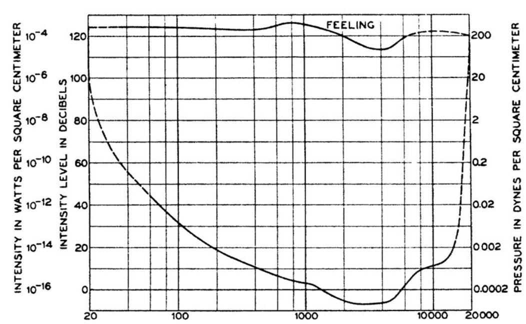
Demonstration

- **Same demo as before: 20 Hz to 20kHz**
  - Instead of thinking about frequency cutoff (range)
  - Think instead about how "loud" the sounds at different frequencies are…
    - Which 'band' sounds 'loudest' to you?
    - Note: they are all at same amplitude, so equally intense
    - But we perceive sounds in 1 kHz to 5 kHz to be louder!

42

42

Auditory Thresholds – Measured by Fletcher

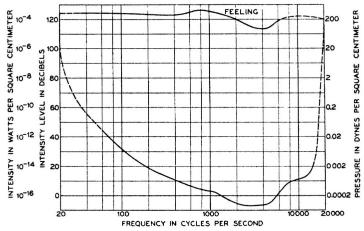


43

43

Quantization and Auditory Thresholds

- **What does this tell us about amplitude quantization?**
  - How much need?
  - Where may need lower or higher quantization?



44

44

Big Ideas

- **Human hearing mechanism directly encodes frequency**
  - By position on Cochlea
  - Frequency domain representation is the natural one
- **Differential sensitivity by frequency**
  - Hear some frequencies louder than others
  - Useful to work with frequency representation to determine
    - What's important to keep
    - What can discard

45

45

Learn More

- **PSYC3320 – Neural Systems and Behavior**
  - Includes visual, audio, olfactory
- **LING2210 – Phonetics 1**
  - Focus on speech, includes both hearing and production

46

46

Admin/Coming up

- **Feedback (including lab from Monday)**
- **Monday:**
  - No Lecture
  - Will be a lab – Convert to Frequency Domain
- **Wednesday**
  - No lecture
- **Next Lecture: Monday 2/20, Fourier Transform**

47

47

References

- **Physical Ear:**
  - R. Munkong and B.-H. Juang. IEEE Sig. Proc. Mag., 25(3):98–117, 2008
- **Filter Bank:**
  - http://www.ugr.es/~atv/web_ci_SIM/en/seccion_4_en.htm
- **Bark Scale:**
  - [E. Zwicker. J. Acoust. Soc.Am., 33(2):248, February 1961]
- **DB Chart:**
  - http://www.dspguide.com/ch22/1.htm

48

48