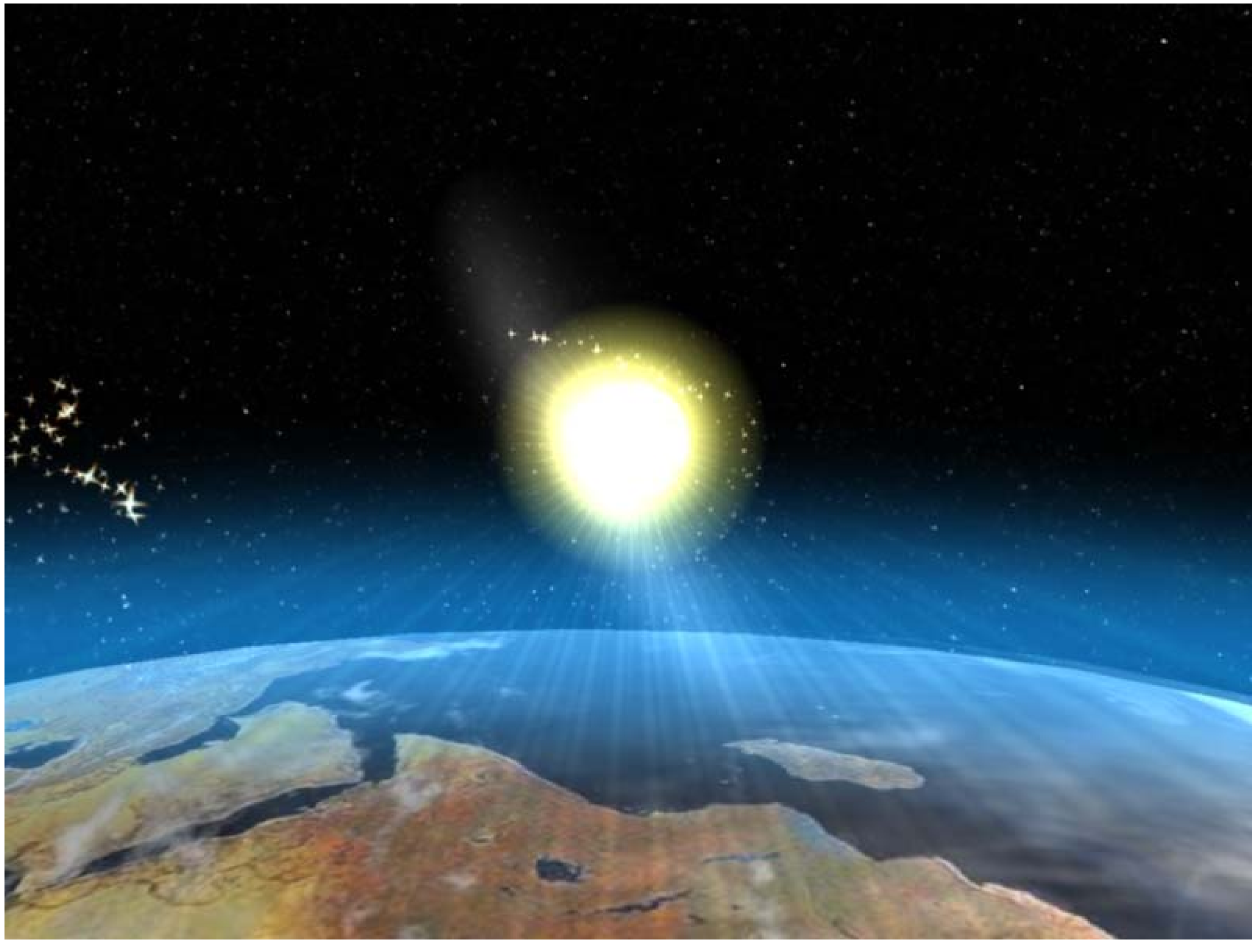
Life & Music on the Third Stone From The Sun



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- Our species – *Homo sapiens* – has been around for ~ 200,000 years – just the “blink of an eye” on geological time-scales –
  Our solar system & the earth are ~ 4.5-4.6 *billion* years old!

- We’re (very) social animals – our social behavior *helped* to bring us out of the “Stone Age” to where we are *today*, living in our high-tech, modern day civilization…

- Our species is ***unique***, in that out of the *billions* of living creatures on this planet, we’re the ***only*** ones who have been driven/curious/ inquisitive enough to have learned (over time) about the nature of the world that we live in, enabling us to “master” our environment…

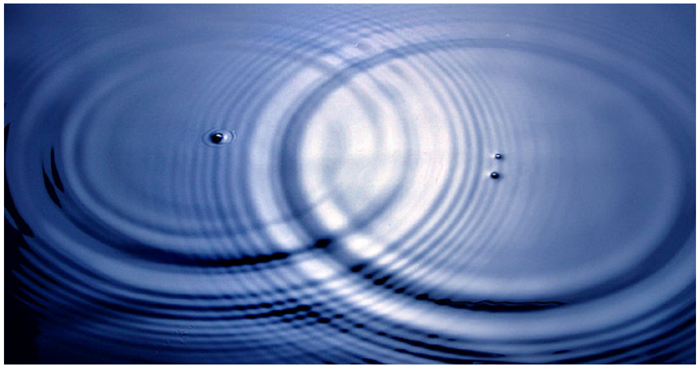
- How does our *music* & our *musical instruments* relate to these issues?

- Our music ***also*** helped to bring us humans out of the "Stone Age" to where we are *today*.
- Recently (~ within the past 2 decades), scientists have learned that participation in/playing music, singing/listening to music:
  - a.) produces many "feel-good" brain chemicals – *serotonin*, *dopamine*, *oxytocin*, …
    (generate feelings of well-being, feelings of trust, reduces feelings of anxiety, …)
  - b.) reduces *cortisol* levels (produced when we're under stress)
  - c.) boosts our *immune system*…
- Music ***may*** have been our first ***language***! Written language is only ~ 6,000 years old. Oral language *much* older. Early human history, important worldly knowledge could ***only*** be passed on by word of mouth (*i*.*e*. orally)…
- The ***first*** human musical instrument was the ***human voice*** – *i*.*e*. ***singing***!
- The 1-D musical instruments we have developed all mimic the human voice, the 2-D musical instruments – drums, percussion instruments – mimic human rhythms!
- Was our earliest human music – *e*.*g*. songs – an important means to preserve/pass on our early human history, worldly knowledge, etc.?
- Does this "naturally" explain why we humans have ***amazing*** abilities to recall ***long-term musical*** memories ***so*** much more powerfully than ***everyday*** memories? Musical memories are stored in ***multiple*** locations in the brain, "everyday" memories are ***not***…

- Human beings – *Homo sapiens* – we *are* social animals.
- We're also ***anthropocentric*** creatures
  – *i.e*. we're *primarily* interested in our ***own*** species...
- This fact has consequences in terms of human hearing & our brain's processing sounds...
- The *ability* to *hear* sounds (like vision) *only* exists because there exist sounds to be *heard* (objects to be *seen*) in our world.
  Very useful "information" *e.g*. for finding food, keeping us safe, *etc*.
- We live in a 3-D world: two ears/two eyes are the minimum needed to locate sounds/objects in the 3-D world.
- No accident that we hear sounds ~ in the range of the human voice, ~ 20 Hz – 20 KHz.

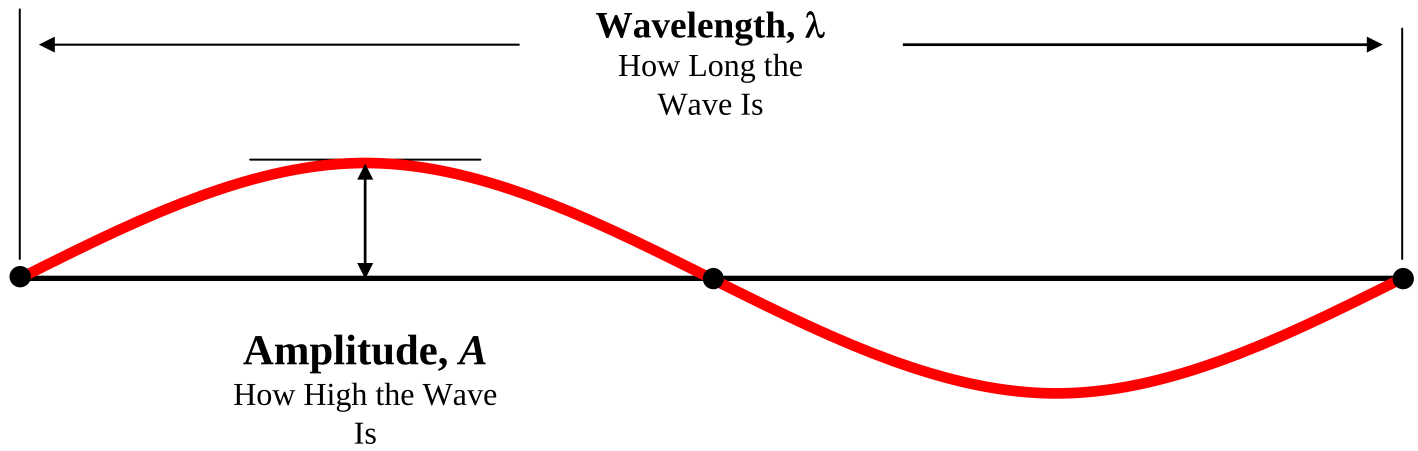
How are sounds produced?

- Some object (= sound source) has to vibrate mechanically.
- Object’s vibrations transfers energy to the surrounding air molecules causing them to vibrate too – sound waves (= an *excess* of energy) propagate out in all directions away from the sound source (= vibrating object).
- If have two (or more) sound sources simultaneously – can give rise to interesting wave interference effects!



Basics of Waves:

Snapshot at time t = 0:



Single Frequency, *f*
How Many Wave Vibrations Each Second

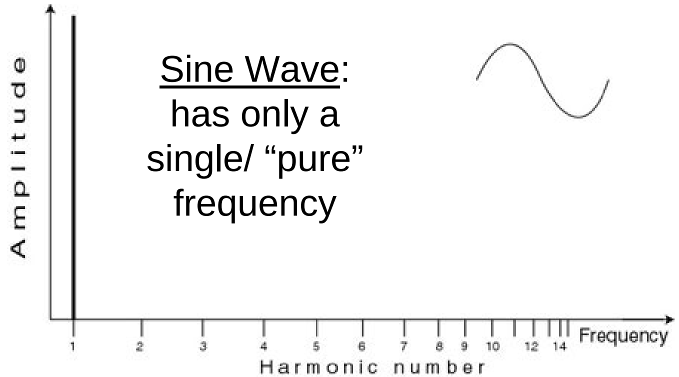
Wave Propagation Speed: $v = f\,\lambda$

Speed of sound in air:
v_{air} **~ 345 m/s ~ 770 *mph* = Mach 1**

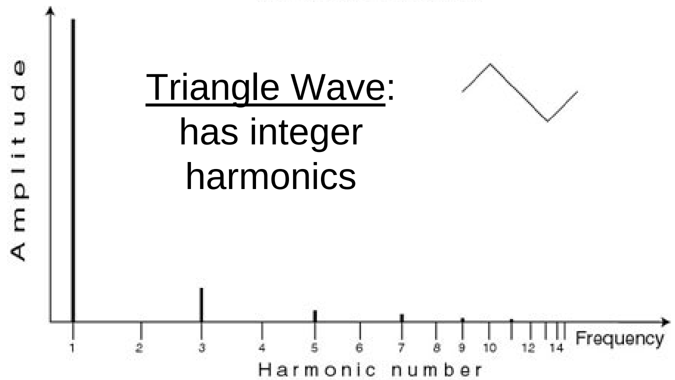
Pressure Wave Propagation:

$$P\,(x, t) = A\,\sin[2\pi(\,x/\lambda \pm f\,t\,)]$$

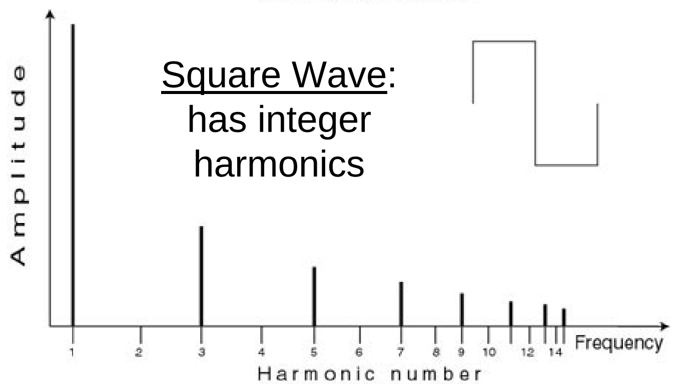
Different Kinds of (Basic) Sound Waves:



Sine Wave: has only a single/ "pure" frequency

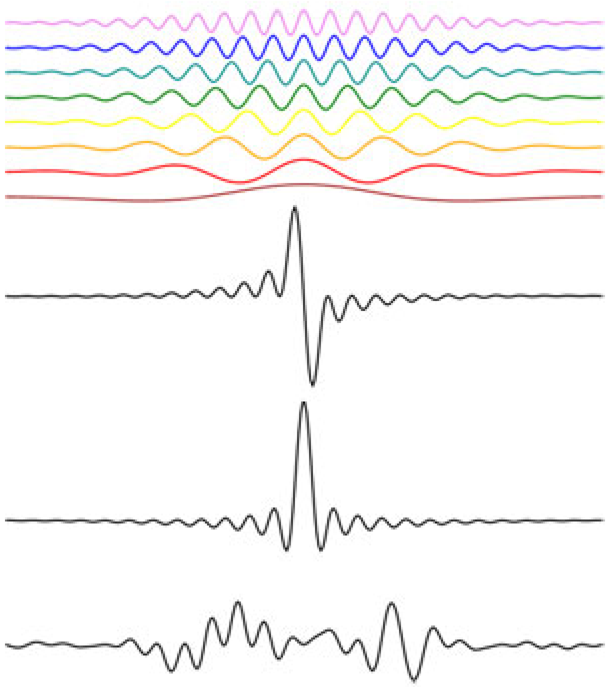


Triangle Wave: has integer harmonics

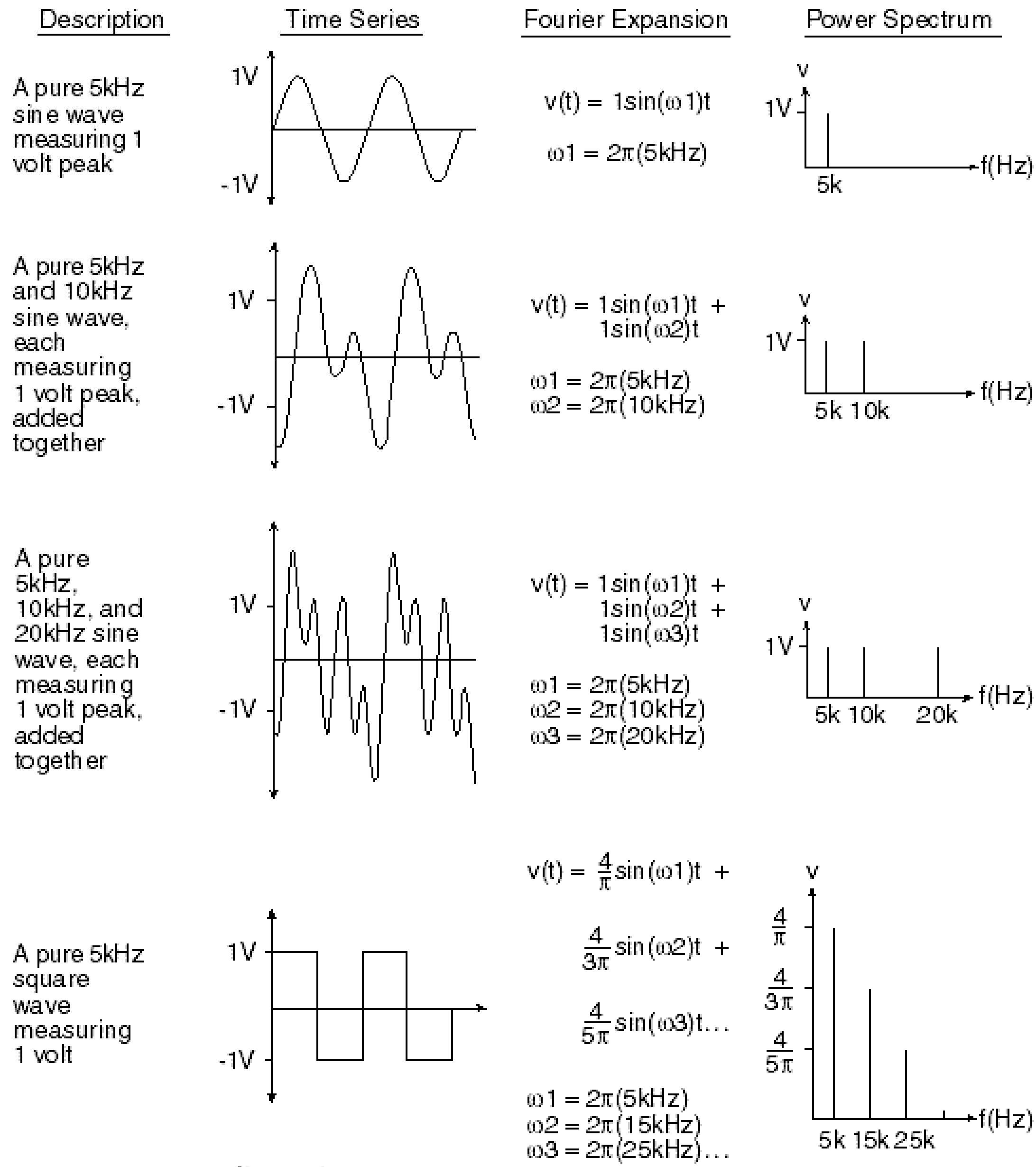


Square Wave: has integer harmonics

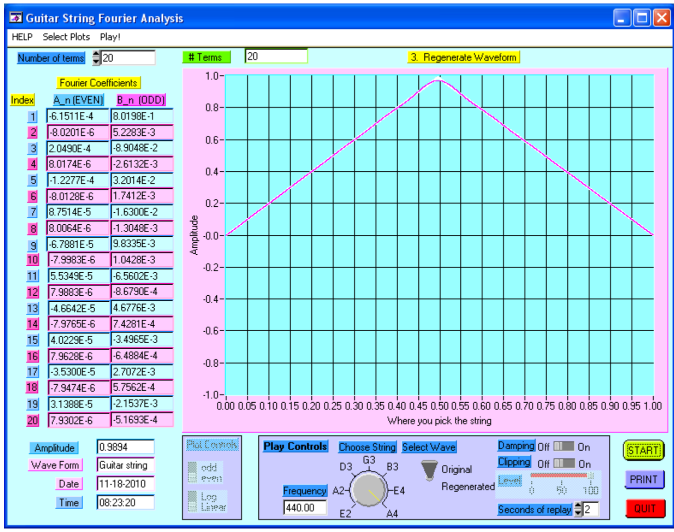
Waveform Synthesis: Adding together a linear combination of harmonics with suitably chosen amplitudes (and phases) we can create any arbitrary waveform!!!

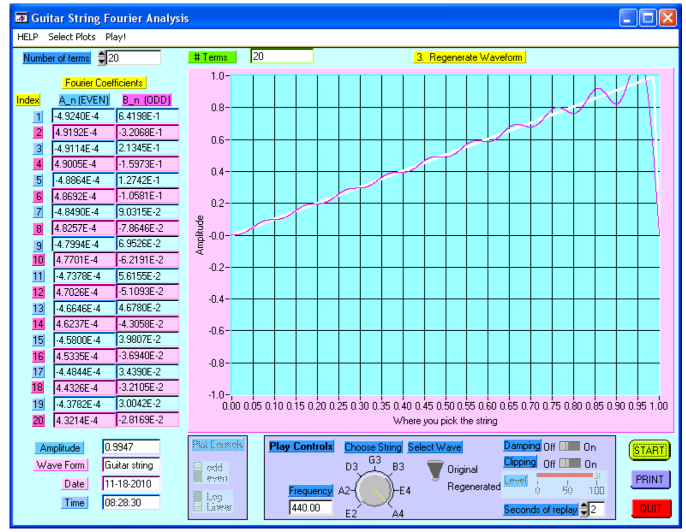


- The ***inverse*** of waveform ***synthesis*** is waveform ***analysis***.
- A ***periodic*** waveform can be *decomposed* into its ***harmonic*** components!
- Branch of mathematics known as *Fourier analysis*.

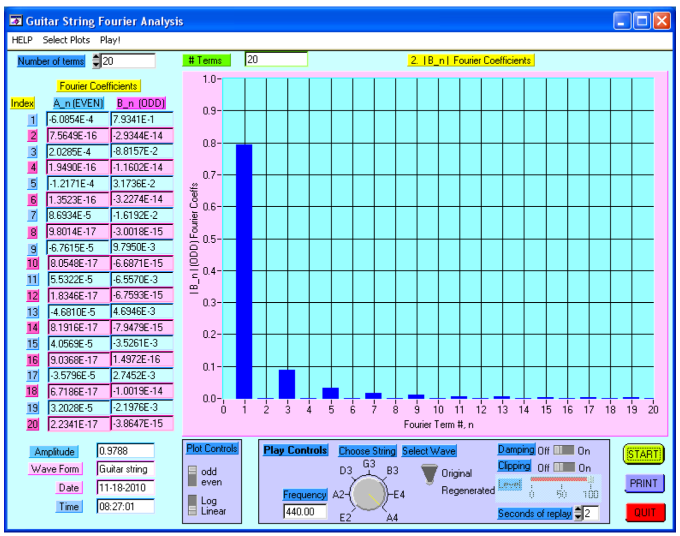


Geometric configuration of vibrating object ***uniquely*** specifies harmonic content!

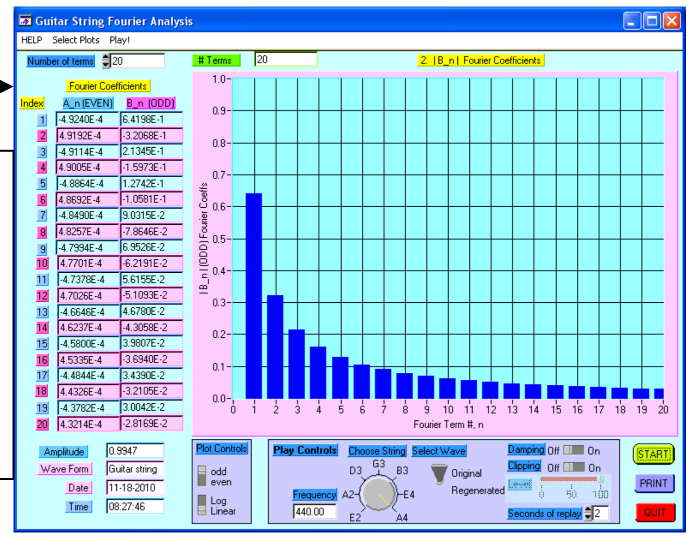




Guitar string plucked @ *midpoint* of string has *mellow* sound because *apex* of triangle doesn't have *much* of a "break" to it – only need *low-order* harmonics to replicate shape of this string



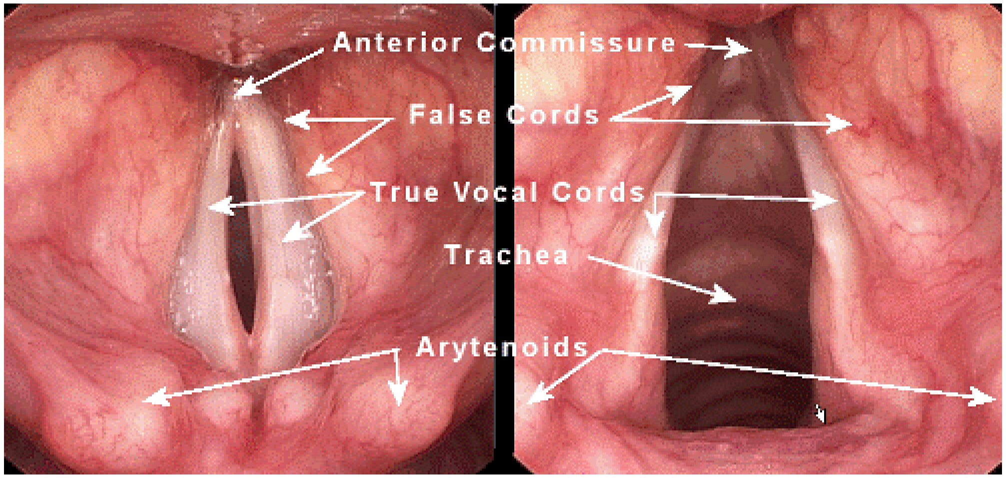
Guitar string plucked near *bridge* has *bright* sound because *apex* of triangle has *much sharper* "break" to it – need *many more* harmonics to replicate shape of this string!



⟹ Harmonic analysis of sound enables one to reconstruct how object is vibrating!

The Human Voice

- Human vocal cords vibrate as a **1-D system**.
- This has profound consequences!
- When a 1-D mechanical system vibrates, there are many *resonant* frequencies of vibrations which (*because* 1-D) are ***integer*** multiples of the lowest resonance frequency (the fundamental):



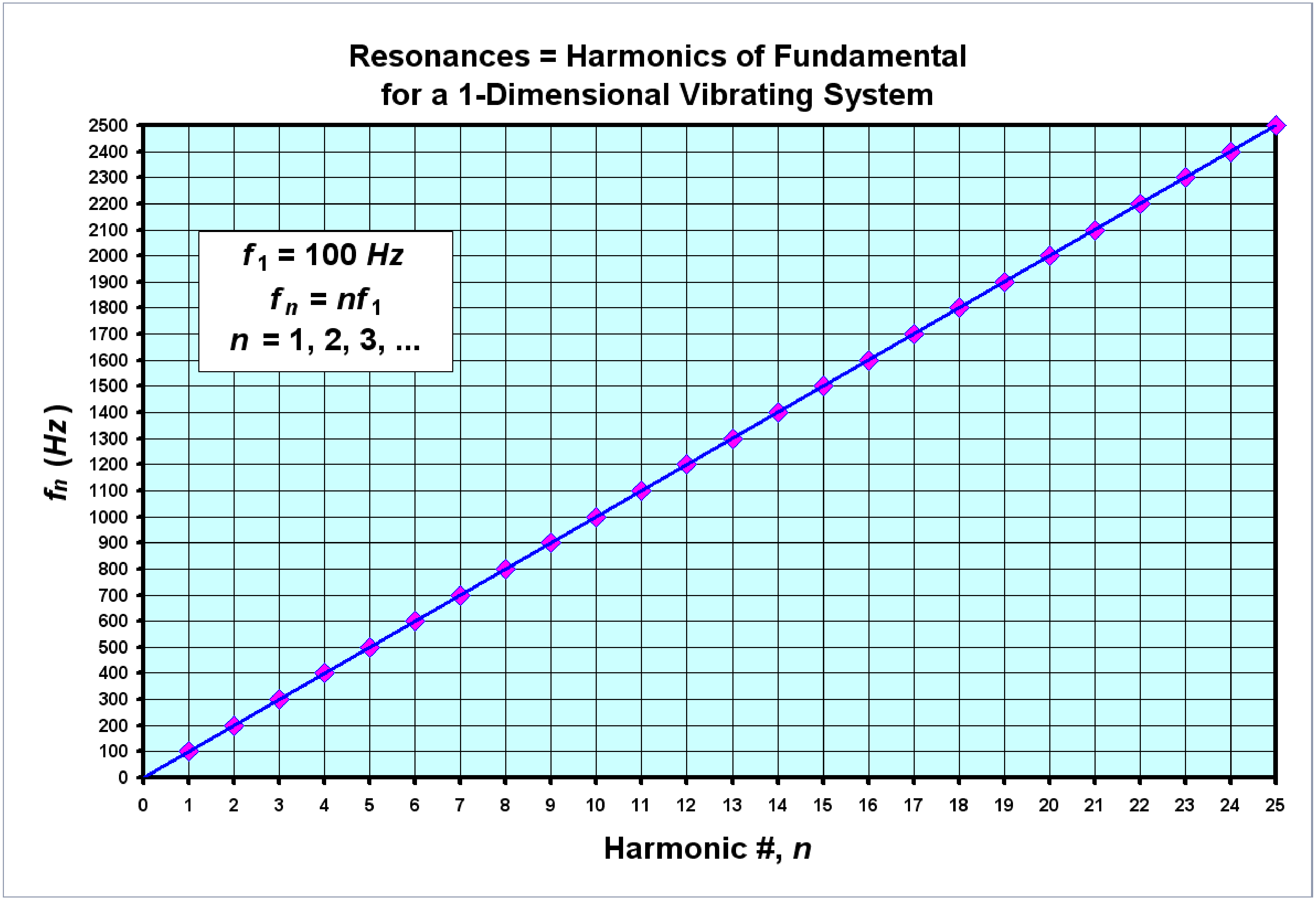
$$f_n = n \cdot f_1,\ n = 1,2,3,\ldots$$

f_n = harmonics of fundamental, f_1

This is a simple, *linear* mathematical relation for straight line w/ intercept, b = 0:

$$y(x) = mx$$

shown graphically next slide:


Resonances = Harmonics of Fundamental
for a 1-Dimensional Vibrating System
f_1 = 100 Hz
$f_n = nf_1$
n = 1, 2, 3, ...
f_n (Hz)
Harmonic #, n
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
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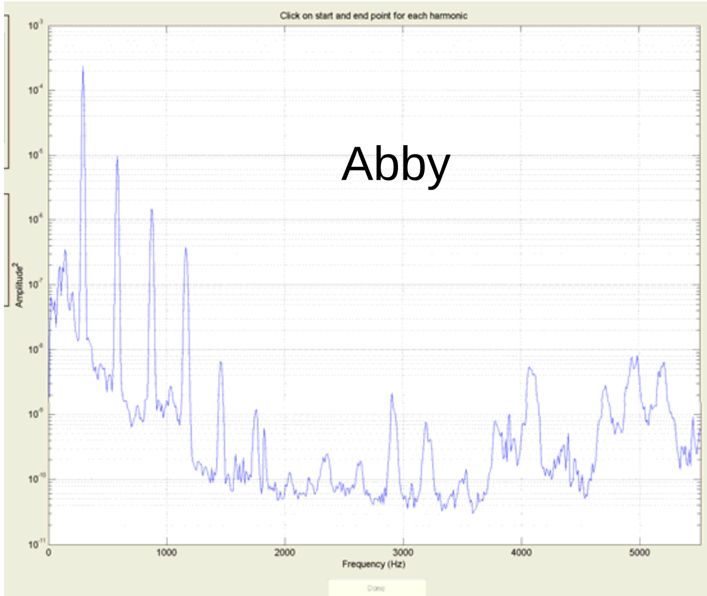
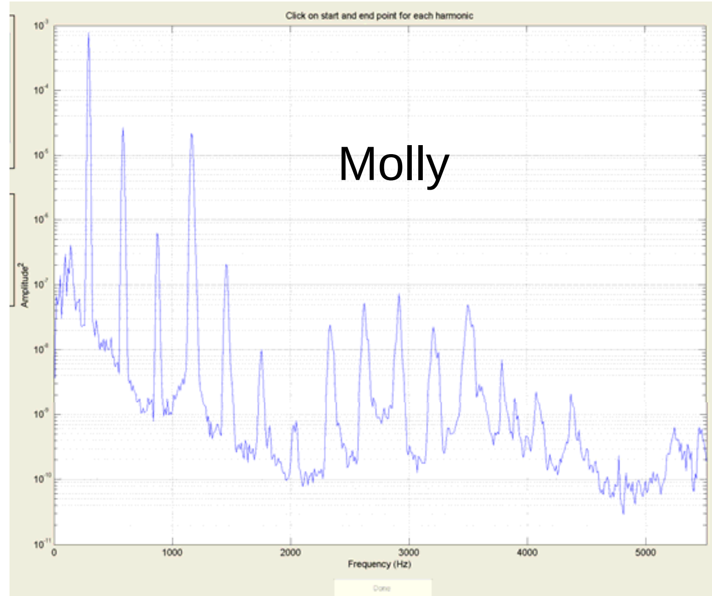
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25

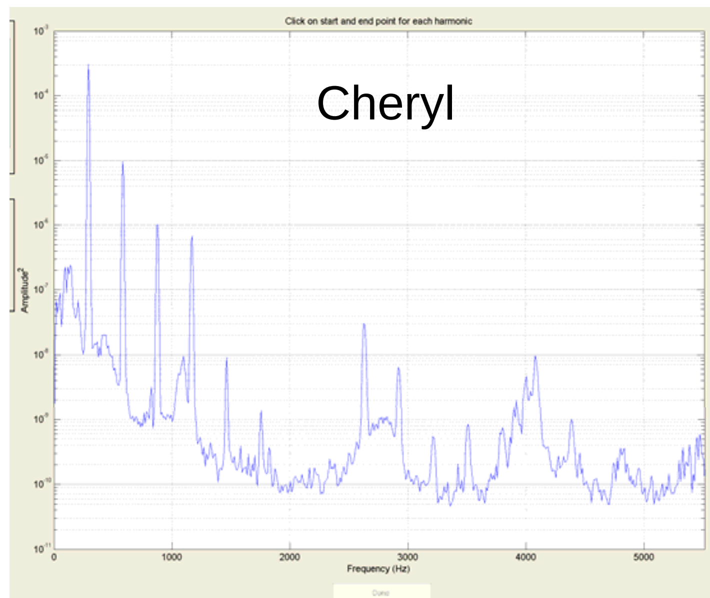




Harmonic Analysis
Human Voices
(semi-log) plots of

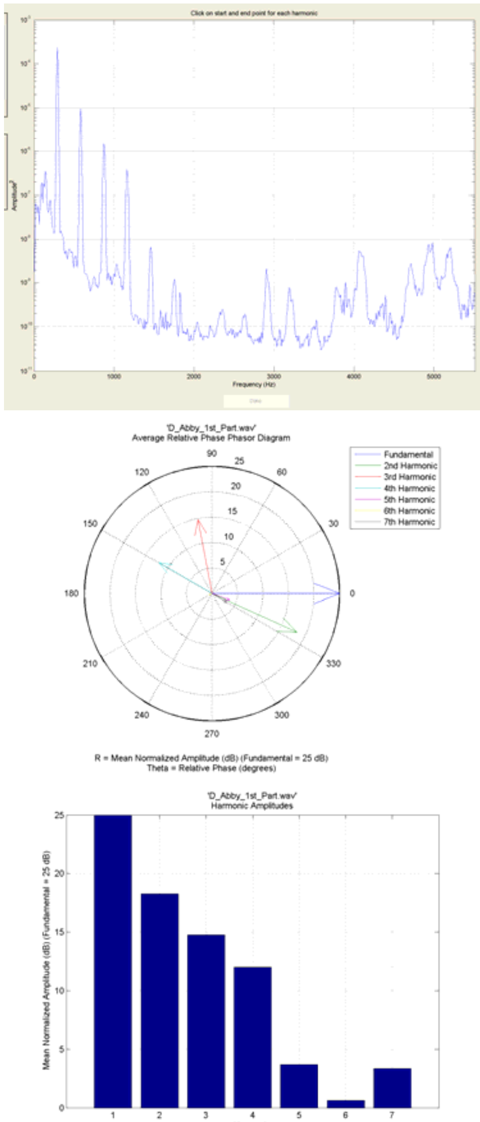
Log (amplitude)^2 *vs*. frequency, f

3 women in UIUC Physic 193 POM course singing "Oooooh" on note D4 (f = 293.66 Hz)

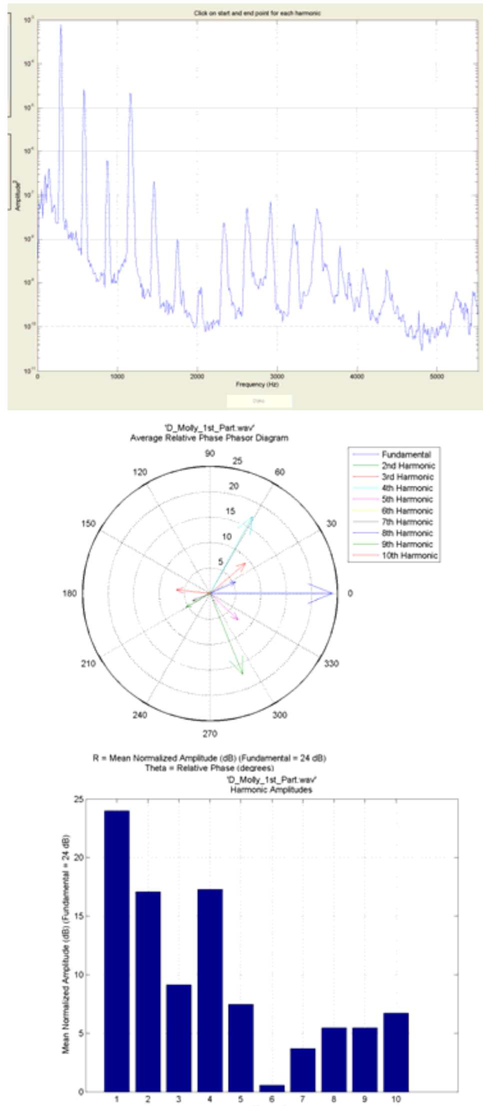


Comparison of 3 UIUC Physics 193 POM women's choir students singing D4 "Oooo" (293.66 Hz):

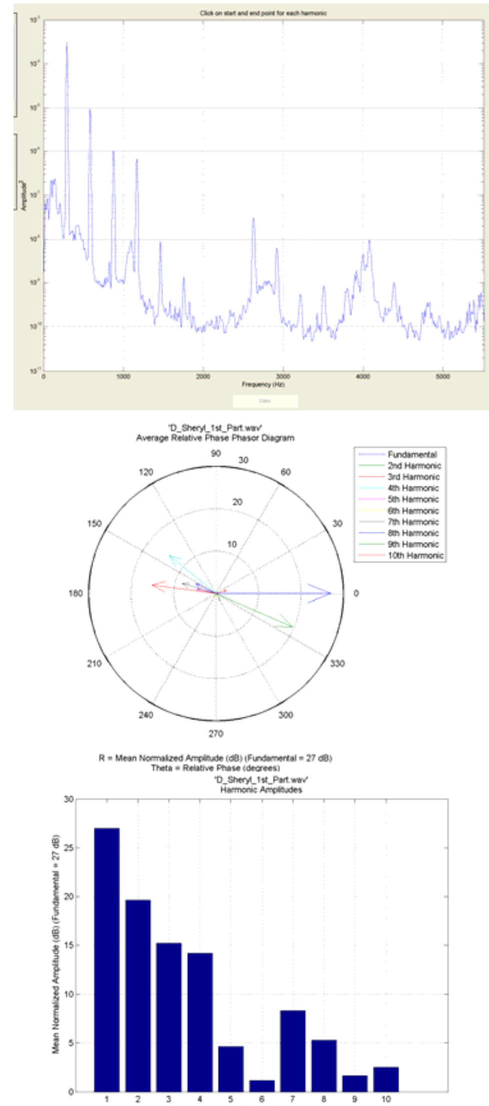
Abby



Molly



Cheryl



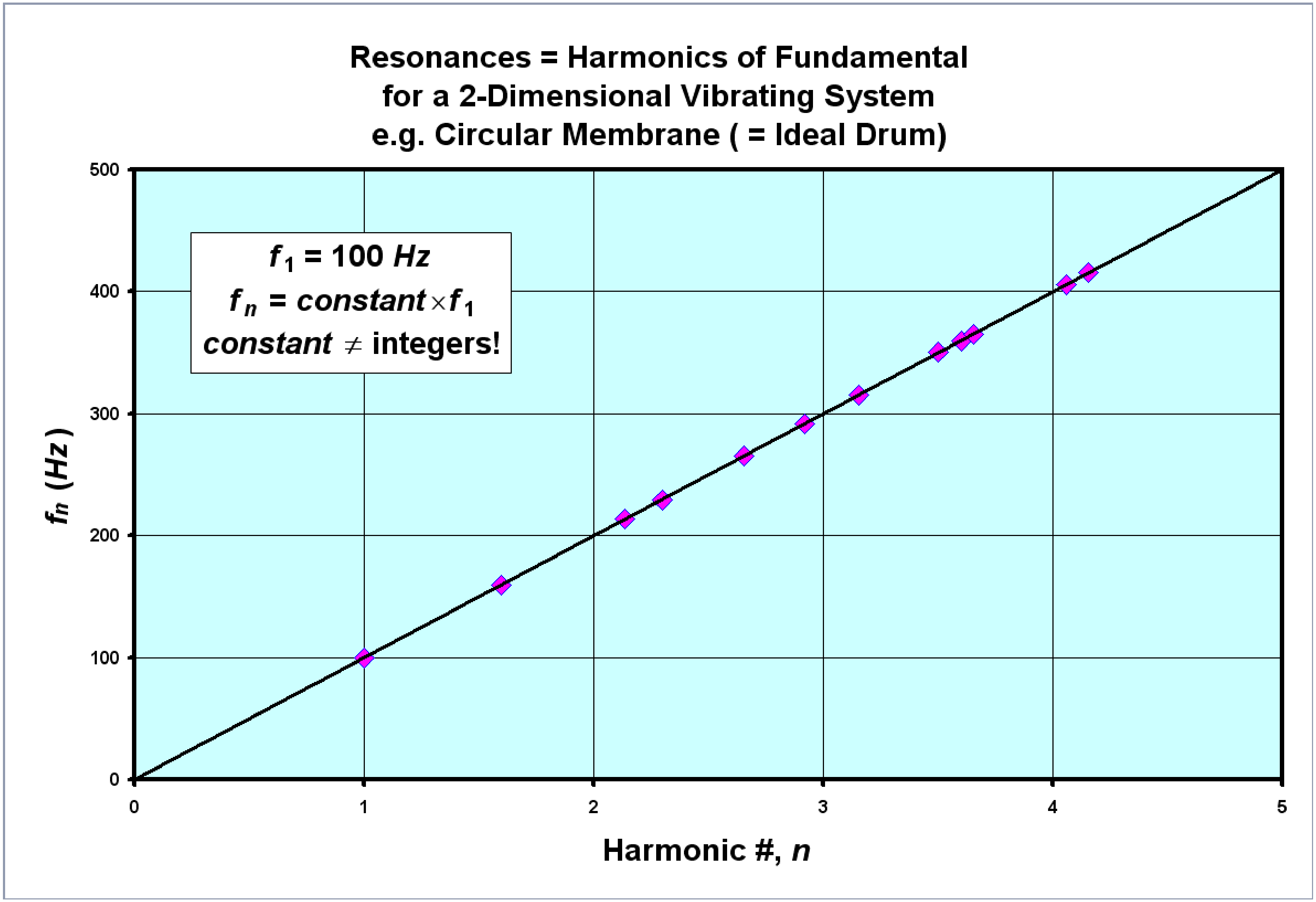
Modes of Vibration of 2-D and 3-D Systems

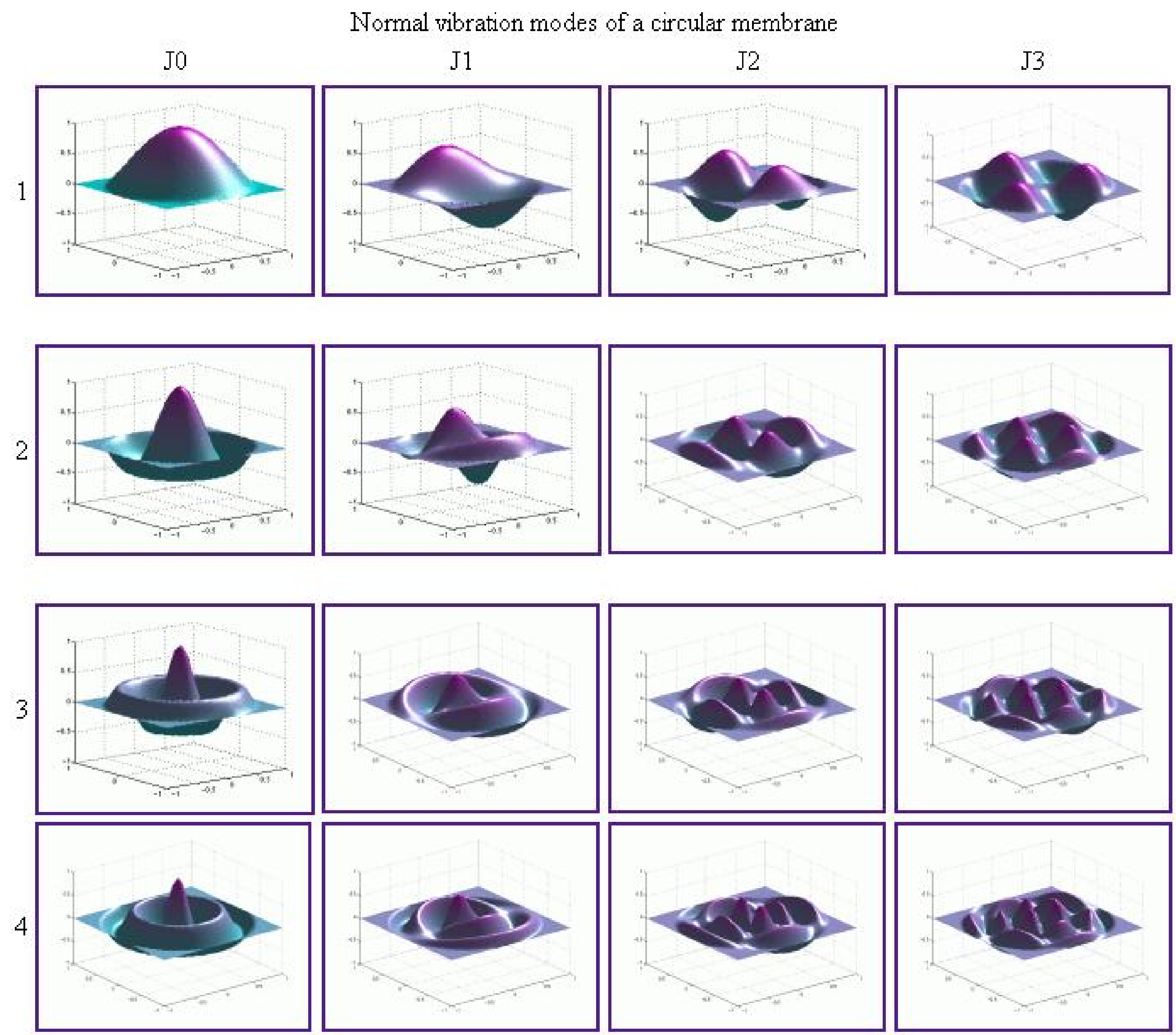
- Vibrational resonances (modes) of a 2-D system have 2 integers: ***n***,***m*** – *e*.*g*. 2-D vibrations of circular drum head.

- Vibrational resonances (modes) of a 3-D system have 3 integers: ***n***,***l***,***m*** – *e*.*g*. 3-D sound waves propagating in our own sun!

- In 2-D or 3-D, higher harmonics of the *fundamental* (*i*.*e*. the lowest frequency) are ***not*** simply integer-multiple related to the *fundamental* frequency. {see next slide}

- Our human voices would sound ***profoundly*** different if we had 2-D or 3-D voice boxes instead of 1-D vocal chords!!!


Resonances = Harmonics of Fundamental
for a 2-Dimensional Vibrating System
e.g. Circular Membrane (= Ideal Drum)
f_1 = 100 *Hz*
f_n = *constant* × f_1
constant ≠ integers!
500
400
300
200
100
0
0
1
2
3
4
5
f_n (*Hz*)
Harmonic #, *n*


Normal vibration modes of a circular membrane
J0
J1
J2
J3
1
2
3
4

The "Natural" Origin of Our Musical Scale

- Because our human vocal cords vibrate as a 1-D system, our voices/singing have *integer*-related harmonic content: $f_n = n \cdot f_1$

- 2^{nd} harmonic $f_2 = 2f_1$: Octave
- 3^{rd} harmonic $f_3 = 3f_1$: Octave + 5^{th}
- 4^{th} harmonic $f_4 = 4f_1$: 2 Octaves
- 5^{th} harmonic $f_5 = 5f_1$: 2 Octaves + Maj. 3^{rd}

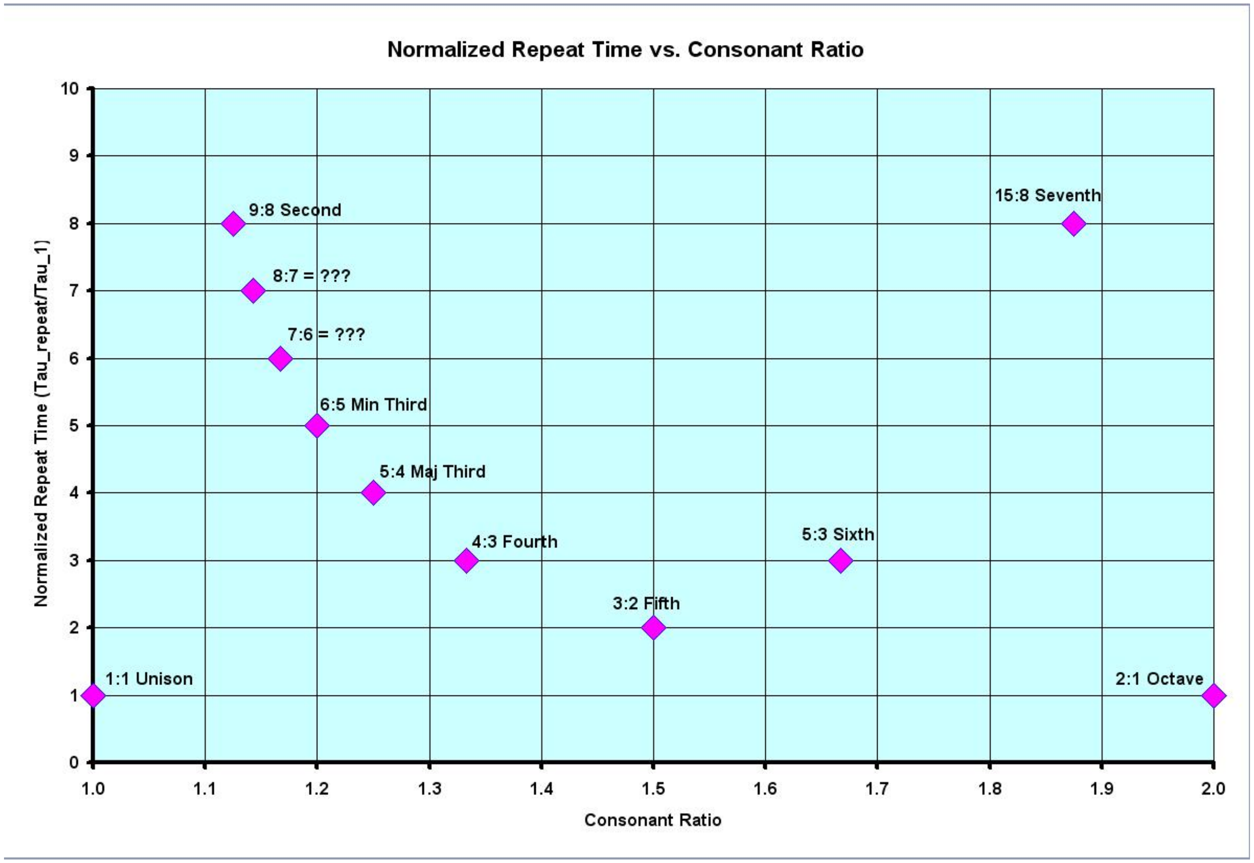
- We humans (like all other animals) are **primarily** interested in our **own** species (*i.e*. we're ***anthropocentric***).

- We (especially) like the sounds our own voices make!

Consonance & Dissonance

- ***Amazing*** things happen when add two sound waves together, whose frequencies are related by the ratio of two *exact* integers – *e.g*. $3f_1$ and $2f_1$ – this ratio is 3:2 – *i.e*. this is a (*perfect*) 5^{th}.
- Resulting waveform = sum of these two sound waves is *phase-stable* (*i.e*. doesn't change in time) – it also has (very) short *repeat period*, it is very *easy* for human beings to analyze this sound.
- Also true for other two sound wave combinations with other *exact* integer frequency ratios such as 4:3 (4^{th}), 5:4 (Maj. 3^{rd}), 6:5 (Min. 3^{rd}), 2:1 (Octave), 1:1 (Unison), etc. = ***consonant*** sounds.
- Adding two sound waves together that do ***not*** have (low-order) *exact* integer ratios do ***NOT*** have these "magical" properties – not phase-stable, they can have very long repeat times, systematically they are also much harder for human brains to analyze. These are none other than the ***dissonant*** ("Non-Human-like") sounds!
- In fact our brains have ***two*** *independent* processing centers for analyzing sounds – one for detecting ***consonant*** sounds – *exact* integer frequency ratios – "Human-like" sounds, and another for detecting ***dissonant*** sounds – sounds ***not*** having *exact* integer frequency ratios – "Non-Human-like".
- Furthermore, the auditory processing centers in our brain are in turn wired into our ***emotional centers*** – which explains why we "enjoy" consonant ("Human-like") sounds whereas we "dislike" dissonant (Non-Human-like) sounds.
- Consonant musical sounds ***can*** make us feel happy, sad, joyful, angry, fearful *etc*. => Explains (in part) *why* music ***is universal*** to ***all*** human beings!

Normalized Repeat Times for *Consonant* Sounds



n.b. Non-consonant/dissonant sounds have ***much*** longer repeat times than consonant sounds.

The Phenomenon of Consonance & Dissonance – Studied by Greek philosophers – using the monochord:

Two frequencies associated with the vibrating string segments:

$$f_x = v/2x \quad f_{L-x} = v/2(L-x)$$

Consonance occurs when frequency ratios = ratio of two integers *m*:*n*
⇒ <u>*phase*</u> <u>*stable*</u> waveforms, e.g:

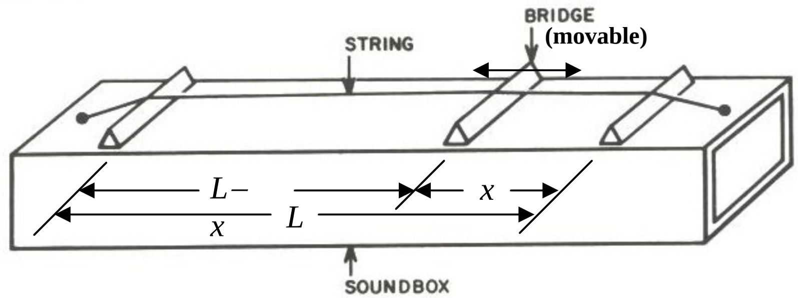
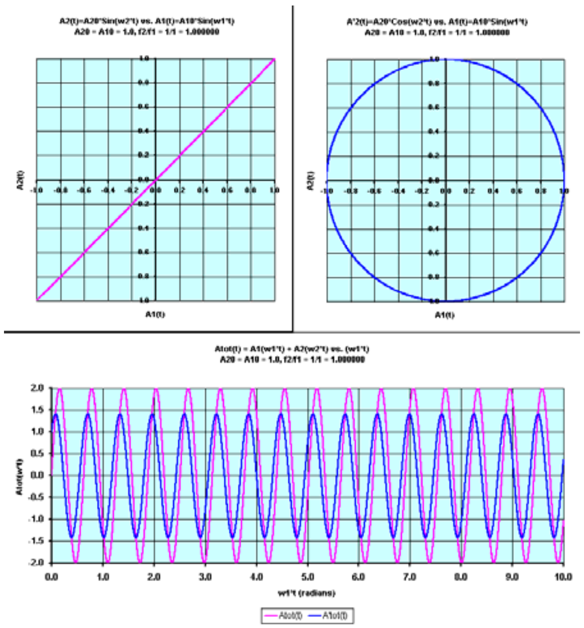


FIG. 1. The monochord.

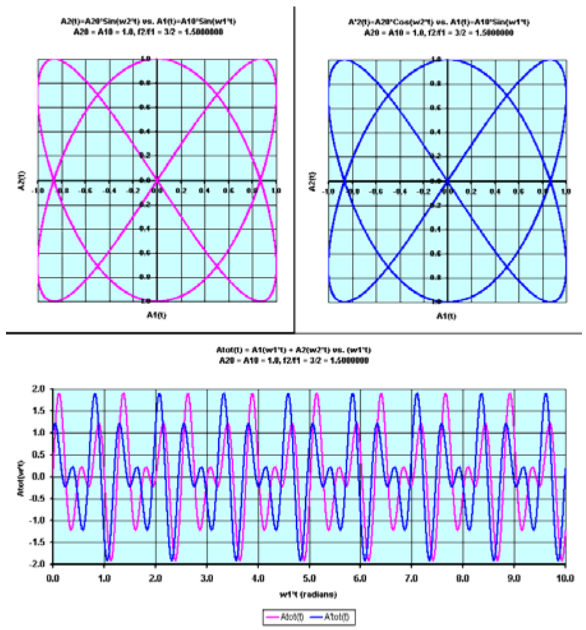
Unison {1:1}

In-Phase: **Quadrature:**



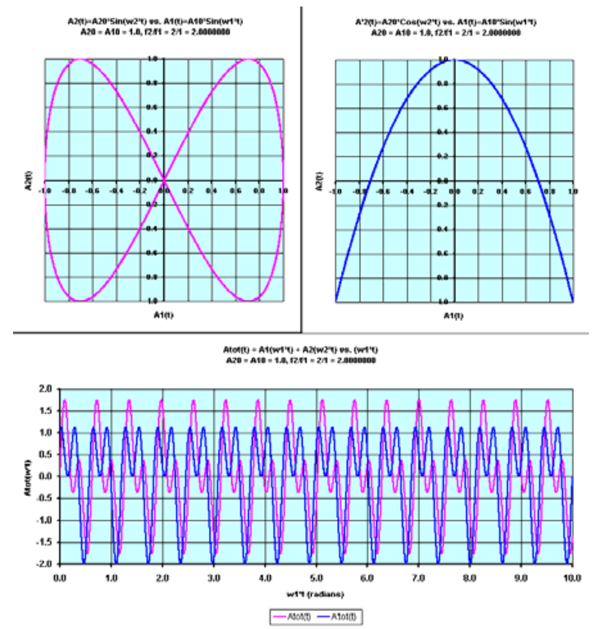
Major Fifth {3:2}

In-Phase: **Quadrature:**



Octave {2:1}

In-Phase: **Quadrature:**



Musical Scales From Consonant Intervals

- We humans perceive *consonant* intervals as “special”, as well as aesthetically pleasing / enjoyable to listen to...
- The pentatonic (5 note) & pythagorean (7 note) and the just diatonic (12 note) “natural” scales are all constructed using *consonant* intervals. See next slide…
- Greeks ~ 3000 years ago are often given credit for developing our musical scales. But see 3rd slide after this one…
- “Natural” Musical scales constructed from consonant intervals are not “perfect” – all suffer from (the fundamental) problem of non-equal intervals between adjacent/successive notes on the musical scale. Presents serious problems for playing music in *different* keys – doesn’t sound the same!
- Tempered 12-note musical scale distributes the “blame” equally among all 12 notes, intervals now all the same. Now can play any music in any key and it will sound equally “bad” (to professional musicians) in any key!

Constructing Musical Scales from Consonant Intervals

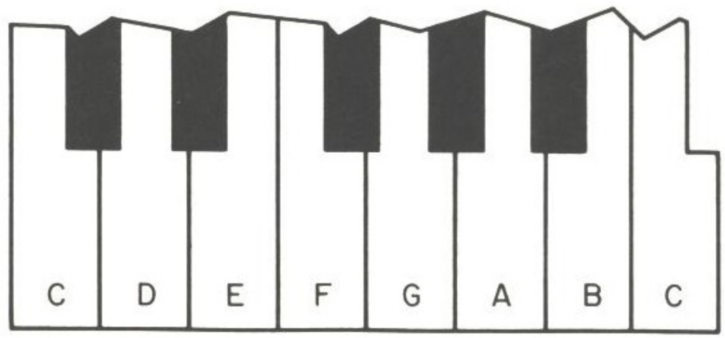


FIG. 2. A portion of the piano keyboard.

The 5-Note (Major) Pentatonic Scale:

Relative Ratio (to fundamental):	1	$^9/_8$	$^4/_3$	$^3/_2$	$^{27}/_{16}$	**2**
Note:	C	D	F	G	A	C
Frequency:	f	$\frac{9}{8}f$	$\frac{4}{3}f$	$\frac{3}{2}f$	$\frac{27}{16}f$	$2f$

FIG. 3. A pentatonic scale.

Interval (Frequency Ratio): $^9/_8$ $^{32}/_{27}$ $^9/_8$ $^9/_8$ $^{32}/_{27}$

The 7-Note Pythagorean Scale:

Note:	C	D	E	F	G	A	B	C
Frequency:	1	$\frac{9}{8}$	$\frac{81}{64}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{27}{16}$	$\frac{243}{128}$	2

Interval: $\frac{9}{8}$ $\frac{9}{8}$ $\frac{256}{243}$ $\frac{9}{8}$ $\frac{9}{8}$ $\frac{9}{8}$ $\frac{256}{243}$

FIG. 4. The Pythagorean scale.

The just diatonic scale gets all the white keys *and* the black ones on the piano…

Our notion of musical scales (& circle of fifths) is <u>intimately</u> connected to consonant intervals:

Note:	C	D	F	G	A	C
Frequency:	f	$\frac{9}{8}f$	$\frac{4}{3}f$	$\frac{3}{2}f$	$\frac{27}{16}f$	$2f$

FIG. 3. A pentatonic scale.

Note:	C		D		E		F		G		A		B		C
Frequency:	1		$\frac{9}{8}$		$\frac{81}{64}$		$\frac{4}{3}$		$\frac{3}{2}$		$\frac{27}{16}$		$\frac{243}{128}$		2
Interval:		$\frac{9}{8}$		$\frac{9}{8}$		$\frac{256}{243}$		$\frac{9}{8}$		$\frac{9}{8}$		$\frac{9}{8}$		$\frac{256}{243}$	

FIG. 4. The Pythagorean scale.

Note:	C		D		E		F		G		A		B		C
Frequency:	1		$\frac{9}{8}$		$\frac{5}{4}$		$\frac{4}{3}$		$\frac{3}{2}$		$\frac{5}{3}$		$\frac{15}{8}$		2
Interval:		$\frac{9}{8}$		$\frac{10}{9}$		$\frac{16}{15}$		$\frac{9}{8}$		$\frac{10}{9}$		$\frac{9}{8}$		$\frac{16}{15}$	

FIG. 8. The just diatonic scale.

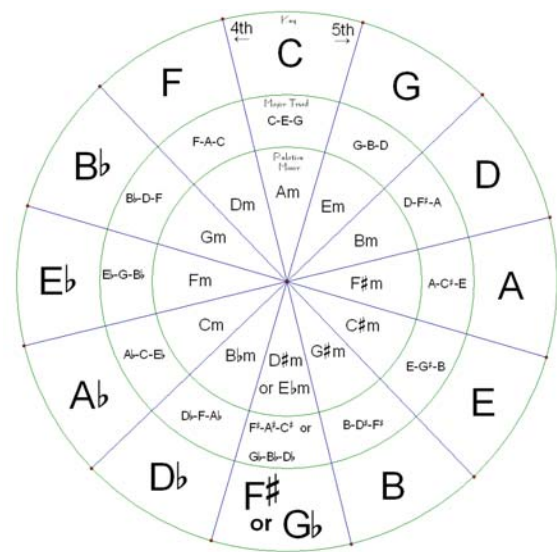
n.b. For musical instruments, if transpose songs in these scales to another key, won't sound the same because the *intervals* between the notes are not the same in all keys….

Musical scale is fundamentally imperfect (consonance perspective):

$a \equiv 2^{1/12}$

C	D♭ / C♯	D	E♭ / D♯	E	F	G♭ / F♯	G	A♭ / G♯	A	B♭ / A♯	B	C
1	a	a^2	a^3	a^4	a^5	a^6	a^7	a^8	a^9	a^{10}	a^{11}	a^{12}
1.000	1.059	1.122	1.189	1.260	1.335	1.414	1.498	1.587	1.682	1.782	1.888	2.000

FIG. 10. The tempered scale.



The Circle of Fifths

Consonance & Dissonance of Complex Tones – Just Diatonic Scale

Consonance of Harmonics - Just Diatonic Scale

Explanation: If two complex tones – e.g. two square or triangle waves and/or two musical tones with integer-related harmonics are superposed/added together – e.g as unison, 2nd, minor 3rd, major 3rd, 4th, 5th, … octave in the just diatonic scale, the colored boxes in the tables below indicate the overlap of harmonics from the two sounds that will be consonant with each other. Thus, e.g. two complex tones in unison, a fifth apart or an octave apart are quite consonant with each other, whereas two complex tones that are e.g. a 2nd or a 7th apart are quite dissonant-sounding.

Fundamental Frequency, f_o = 100 Hz

Harmonic #	Unison C-C 1:1	Second D-C 9:8	??? ???-C 8:7	??? ???-C 7:6	Minor 3rd E_b-C 6:5	Major 3rd E-C 5:4	Fourth F-C 4:3	Fifth G-C 3:2	Sixth A-C 5:3	Seventh B-C 15:8	Octave C-C 2:1
1	100.0	112.5	114.3	116.7	120.0	125.0	133.3	150.0	166.7	187.5	200.0
2	200.0	225.0	228.6	233.3	240.0	250.0	266.7	300.0	333.3	375.0	400.0
3	300.0	337.5	342.9	350.0	360.0	375.0	400.0	450.0	500.0	562.5	600.0
4	400.0	450.0	457.1	466.7	480.0	500.0	533.3	600.0	666.7	750.0	800.0
5	500.0	562.5	571.4	583.3	600.0	625.0	666.7	750.0	833.3	937.5	1000.0
6	600.0	675.0	685.7	700.0	720.0	750.0	800.0	900.0	1000.0	1125.0	1200.0
7	700.0	787.5	800.0	816.7	840.0	875.0	933.3	1050.0	1166.7	1312.5	1400.0
8	800.0	900.0	914.3	933.3	960.0	1000.0	1066.7	1200.0	1333.3	1500.0	1600.0
9	900.0	1012.5	1028.6	1050.0	1080.0	1125.0	1200.0	1350.0	1500.0	1687.5	1800.0
10	1000.0	1125.0	1142.9	1166.7	1200.0	1250.0	1333.3	1500.0	1666.7	1875.0	2000.0
11	1100.0	1237.5	1257.1	1283.3	1320.0	1375.0	1466.7	1650.0	1833.3	2062.5	2200.0
12	1200.0	1350.0	1371.4	1400.0	1440.0	1500.0	1600.0	1800.0	2000.0	2250.0	2400.0
13	1300.0	1462.5	1485.7	1516.7	1560.0	1625.0	1733.3	1950.0	2166.7	2437.5	2600.0
14	1400.0	1575.0	1600.0	1633.3	1680.0	1750.0	1866.7	2100.0	2333.3	2625.0	2800.0
15	1500.0	1687.5	1714.3	1750.0	1800.0	1875.0	2000.0	2250.0	2500.0	2812.5	3000.0
16	1600.0	1800.0	1828.6	1866.7	1920.0	2000.0	2133.3	2400.0	2666.7	3000.0	3200.0
17	1700.0	1912.5	1942.9	1983.3	2040.0	2125.0	2266.7	2550.0	2833.3	3187.5	3400.0
18	1800.0	2025.0	2057.1	2100.0	2160.0	2250.0	2400.0	2700.0	3000.0	3375.0	3600.0
19	1900.0	2137.5	2171.4	2216.7	2280.0	2375.0	2533.3	2850.0	3166.7	3562.5	3800.0
20	2000.0	2250.0	2285.7	2333.3	2400.0	2500.0	2666.7	3000.0	3333.3	3750.0	4000.0
21	2100.0	2362.5	2400.0	2450.0	2520.0	2625.0	2800.0	3150.0	3500.0	3937.5	4200.0
22	2200.0	2475.0	2514.3	2566.7	2640.0	2750.0	2933.3	3300.0	3666.7	4125.0	4400.0
23	2300.0	2587.5	2628.6	2683.3	2760.0	2875.0	3066.7	3450.0	3833.3	4312.5	4600.0
24	2400.0	2700.0	2742.9	2800.0	2880.0	3000.0	3200.0	3600.0	4000.0	4500.0	4800.0
25	2500.0	2812.5	2857.1	2916.7	3000.0	3125.0	3333.3	3750.0	4166.7	4687.5	5000.0
26	2600.0	2925.0	2971.4	3033.3	3120.0	3250.0	3466.7	3900.0	4333.3	4875.0	5200.0
27	2700.0	3037.5	3085.7	3150.0	3240.0	3375.0	3600.0	4050.0	4500.0	5062.5	5400.0
28	2800.0	3150.0	3200.0	3266.7	3360.0	3500.0	3733.3	4200.0	4666.7	5250.0	5600.0
29	2900.0	3262.5	3314.3	3383.3	3480.0	3625.0	3866.7	4350.0	4833.3	5437.5	5800.0
30	3000.0	3375.0	3428.6	3500.0	3600.0	3750.0	4000.0	4500.0	5000.0	5625.0	6000.0
31	3100.0	3487.5	3542.9	3616.7	3720.0	3875.0	4133.3	4650.0	5166.7	5812.5	6200.0
32	3200.0	3600.0	3657.1	3733.3	3840.0	4000.0	4266.7	4800.0	5333.3	6000.0	6400.0

Dissonance of Harmonics - Just Diatonic Scale

Explanation: If two complex tones – e.g. two square or triangle waves and/or two musical tones with integer-related harmonics are superposed/added together – e.g as unison, 2nd, minor 3rd, major 3rd, 4th, 5th, … octave in the just diatonic scale, the colored boxes in the tables below indicate the overlap of harmonics from the two sounds are within the critical band of the human ear and hence will be dissonant with each other. Thus, e.g. two complex tones in unison, a fifth apart or an octave apart are quite consonant with each other, whereas two complex tones that are e.g. a 2nd or a 7th apart are quite dissonant-sounding.

Fundamental Frequency, f_o = 100 Hz

Harmonic #	Unison C-C 1:1	Second D-C 9:8	??? ???-C 8:7	??? ???-C 7:6	Minor 3rd E_b-C 6:5	Major 3rd E-C 5:4	Fourth F-C 4:3	Fifth G-C 3:2	Sixth A-C 5:3	Seventh B-C 15:8	Octave C-C 2:1
1	100.0	112.5	114.3	116.7	120.0	125.0	133.3	150.0	166.7	187.5	200.0
2	200.0	225.0	228.6	233.3	240.0	250.0	266.7	300.0	333.3	375.0	400.0
3	300.0	337.5	342.9	350.0	360.0	375.0	400.0	450.0	500.0	562.5	600.0
4	400.0	450.0	457.1	466.7	480.0	500.0	533.3	600.0	666.7	750.0	800.0
5	500.0	562.5	571.4	583.3	600.0	625.0	666.7	750.0	833.3	937.5	1000.0
6	600.0	675.0	685.7	700.0	720.0	750.0	800.0	900.0	1000.0	1125.0	1200.0
7	700.0	787.5	800.0	816.7	840.0	875.0	933.3	1050.0	1166.7	1312.5	1400.0
8	800.0	900.0	914.3	933.3	960.0	1000.0	1066.7	1200.0	1333.3	1500.0	1600.0
9	900.0	1012.5	1028.6	1050.0	1080.0	1125.0	1200.0	1350.0	1500.0	1687.5	1800.0
10	1000.0	1125.0	1142.9	1166.7	1200.0	1250.0	1333.3	1500.0	1666.7	1875.0	2000.0
11	1100.0	1237.5	1257.1	1283.3	1320.0	1375.0	1466.7	1650.0	1833.3	2062.5	2200.0
12	1200.0	1350.0	1371.4	1400.0	1440.0	1500.0	1600.0	1800.0	2000.0	2250.0	2400.0
13	1300.0	1462.5	1485.7	1516.7	1560.0	1625.0	1733.3	1950.0	2166.7	2437.5	2600.0
14	1400.0	1575.0	1600.0	1633.3	1680.0	1750.0	1866.7	2100.0	2333.3	2625.0	2800.0
15	1500.0	1687.5	1714.3	1750.0	1800.0	1875.0	2000.0	2250.0	2500.0	2812.5	3000.0
16	1600.0	1800.0	1828.6	1866.7	1920.0	2000.0	2133.3	2400.0	2666.7	3000.0	3200.0
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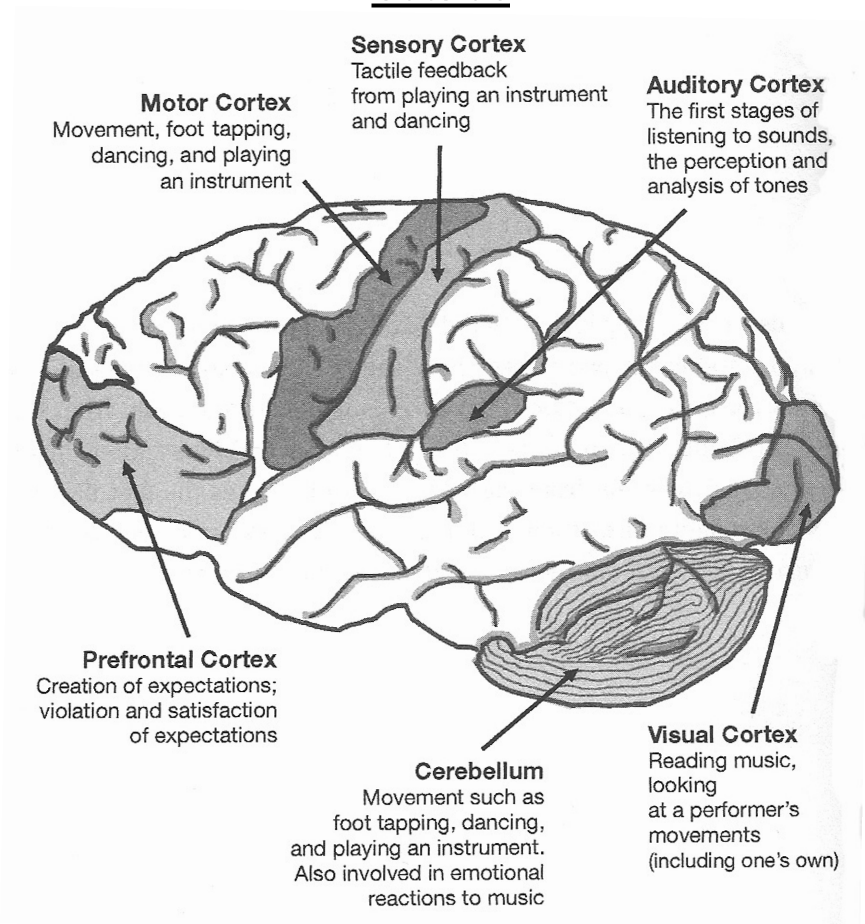
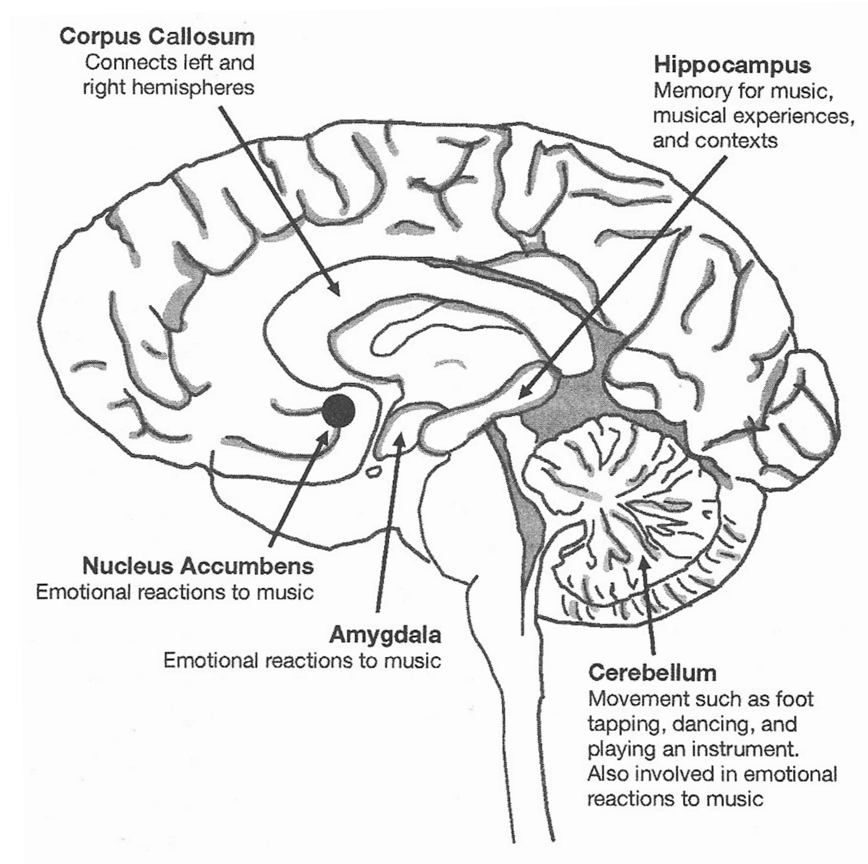
20	2000.0	2250.0	2285.7	2333.3	2400.0	2500.0	2666.7	3000.0	3333.3	3750.0	4000.0
21	2100.0	2362.5	2400.0	2450.0	2520.0	2625.0	2800.0	3150.0	3500.0	3937.5	4200.0
22	2200.0	2475.0	2514.3	2566.7	2640.0	2750.0	2933.3	3300.0	3666.7	4125.0	4400.0
23	2300.0	2587.5	2628.6	2683.3	2760.0	2875.0	3066.7	3450.0	3833.3	4312.5	4600.0
24	2400.0	2700.0	2742.9	2800.0	2880.0	3000.0	3200.0	3600.0	4000.0	4500.0	4800.0
25	2500.0	2812.5	2857.1	2916.7	3000.0	3125.0	3333.3	3750.0	4166.7	4687.5	5000.0
26	2600.0	2925.0	2971.4	3033.3	3120.0	3250.0	3466.7	3900.0	4333.3	4875.0	5200.0
27	2700.0	3037.5	3085.7	3150.0	3240.0	3375.0	3600.0	4050.0	4500.0	5062.5	5400.0
28	2800.0	3150.0	3200.0	3266.7	3360.0	3500.0	3733.3	4200.0	4666.7	5250.0	5600.0
29	2900.0	3262.5	3314.3	3383.3	3480.0	3625.0	3866.7	4350.0	4833.3	5437.5	5800.0
30	3000.0	3375.0	3428.6	3500.0	3600.0	3750.0	4000.0	4500.0	5000.0	5625.0	6000.0
31	3100.0	3487.5	3542.9	3616.7	3720.0	3875.0	4133.3	4650.0	5166.7	5812.5	6200.0
32	3200.0	3600.0	3657.1	3733.3	3840.0	4000.0	4266.7	4800.0	5333.3	6000.0	6400.0

Regions of the Human Brain Associated with Music:

Outside:



Inside:



***Tonotopic* organization of the human auditory cortex – fMRI scans – pitch discrimination circuitry is *geometrically* laid out in ascending order – like keys on a piano!**

24 *D. Bilecen et al. / Hearing Research 126 (1998) 19–27*

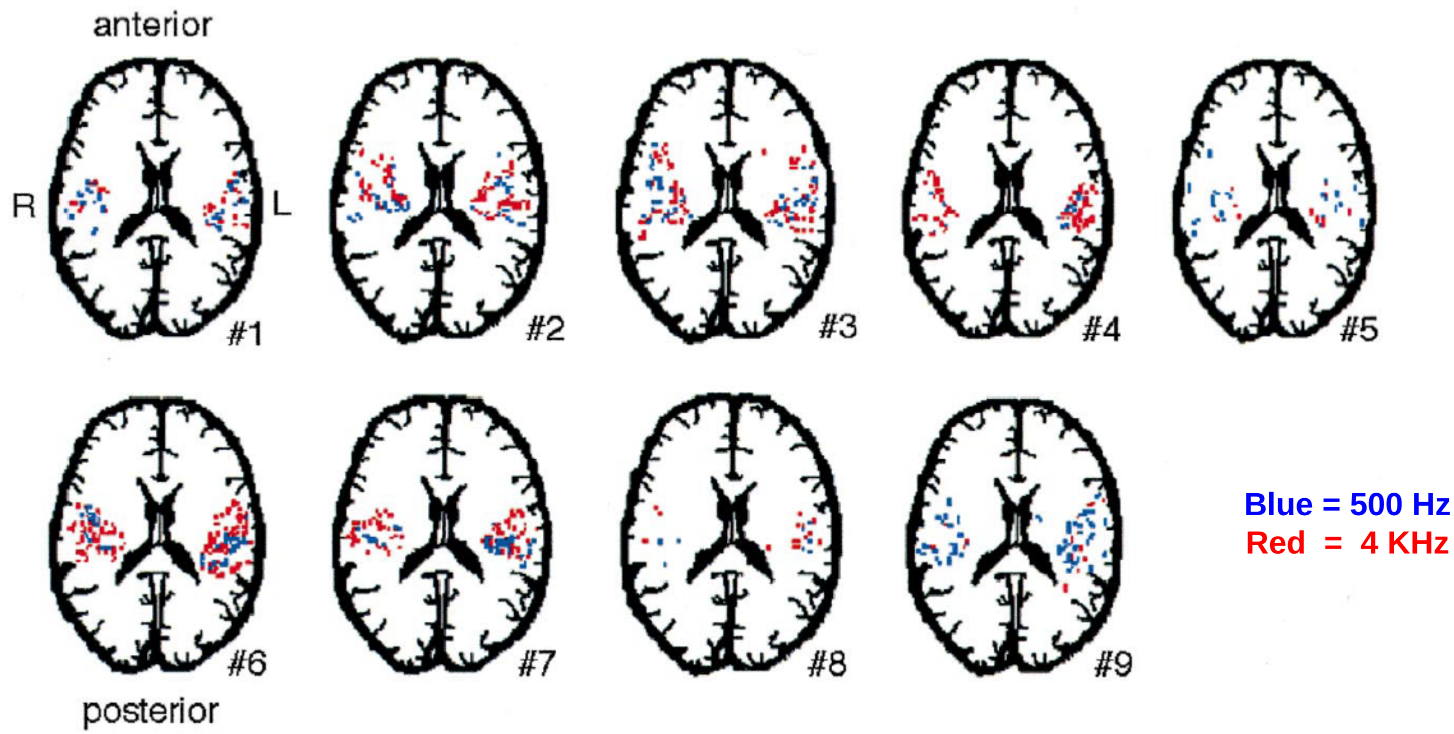
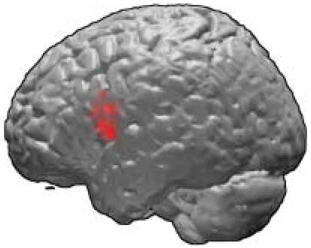


Fig. 5. Activated pixels in axial projection of all nine subjects. Blue pixels represent 500 Hz and red pixels 4000 Hz tone activated areas. All functional images were imposed on a schematic sketch. In general, high tone areas are located more frontally and closer to the medio-sagittal plane than the low tone activated areas.

Genes for Language and Music:

Examination of fossil skulls reveals that Brodmann area 44 (BA44) – part of the frontal cortex {important for cognitive and perceptual tasks, as well as auditory motor imitation via *mirror neurons*} may well have been in place ~ 2 Myrs ago (i.e. long before Homo sapiens – first emerged ~ 200 Kyrs ago).



Brodmann area 44

⇒ Neural mechanisms for *language* were in place *long* before fully exploited…

The FOXP2 gene (located on chromosome 7) is closely associated with human language – also existed in Neanderthals {recent DNA analysis!}. Chimpanzees and songbirds such as the zebra finch {as well as other animals - e.g. fish, mice, crocodiles,…} have their own versions of the FOXP2 gene.

***Microcephalin* is part of the human genome that encodes for brain development. A genetic variant of this gene emerged ~ 37,000 years ago – *i.e.* at the beginning of culturally modern humans, and coincides with the emergence of tonal languages and the appearance of artistic artifacts and bone flutes…**

A second genetic variation of microcephalin arose ~ 5,800 yrs ago – coincides with the first record of written language, spread of agriculture, development of cities, transitioning from hunter-gather to agrarian societies…

***n.b. Social interactions* can/do alter gene expression in the brain {and vice versa}!**

The earliest {unambiguously} known musical instrument – ivory flute (made from woolly mammoth tusk) found in a mountain cave {Geissenklösterle}, near Ulm, in southwestern Germany in 2004, ~ 37,000 years old, and is ~ 18.7 cm long:

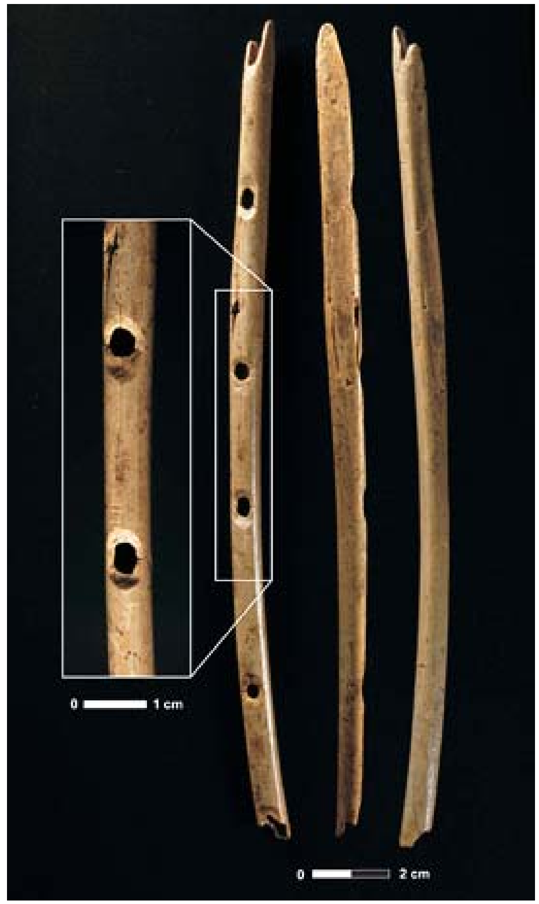
n.b. other flutes (made from swan bones) discovered earlier in same cave;

A bone drumstick has also found in this cave….

Earliest Musical Instruments

Simple bone flutes – such as the one shown in the pix (found in 2008 in a cave near Hohle-Fels, located in southwestern Germany) date back to the Pæleolithic era – *i.e*. ~ 30,000 – 40,000 years ago.

This particular flute has been dated to be at least 35,000 years old, likely it is closer to 40,000 years old!



An ***exact*** replica of this 5-hole bone flute was given to a professional musician, who was able (after a period of time learning how to play it) to play clear renditions of "Amazing Grace" and the German national anthem ("Das Deutschlandlied") on this flute – indicating that early humans at that time already ***<u>must</u>*** have had a clear notion of ***consonant intervals <u>and</u> e.g. the pentatonic and diatonic musical scales***!!!

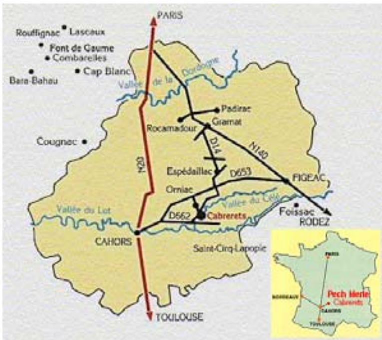
Earliest Musical Instruments

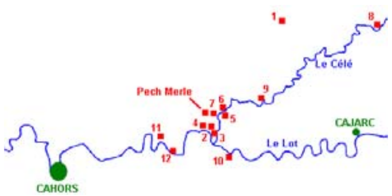
Another of the earliest known musical instruments, again from the Pæleolithic era – *i.e.* ~ 30,000 – 40,000 years ago is the ***turndun*** (*aka* "***bullroarer***") – they are actually *airfoils* (!!!) swung by a rope in a horizontal plane over a person's head – they make a roaring sound, like an airplane propeller blade does!!!

They were used in ritual ceremonies, as well as for long-distance communication.

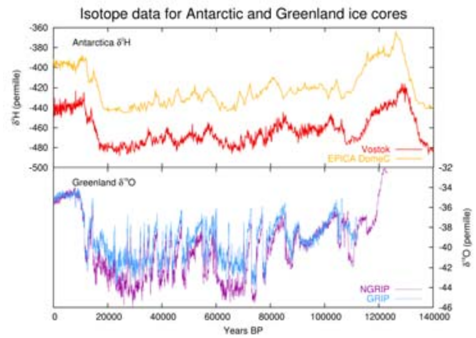
Connection Between Prehistoric Art and Music in Palæolithic Caves:

Grotte du Peche Merle {Blackbird Hill}, Caberets, Departement Lot, Southern France



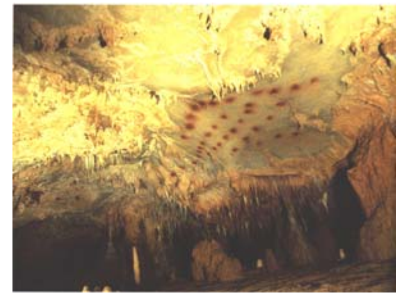


Caves were a good place to live / camp out in during the last glacial period:



Paintings dated ~ 20,000 – 25,000 yrs old

Red dots are markers for acoustic resonances !!!



La Grotte du Portel, Ariège Pyrenees, Southern France:

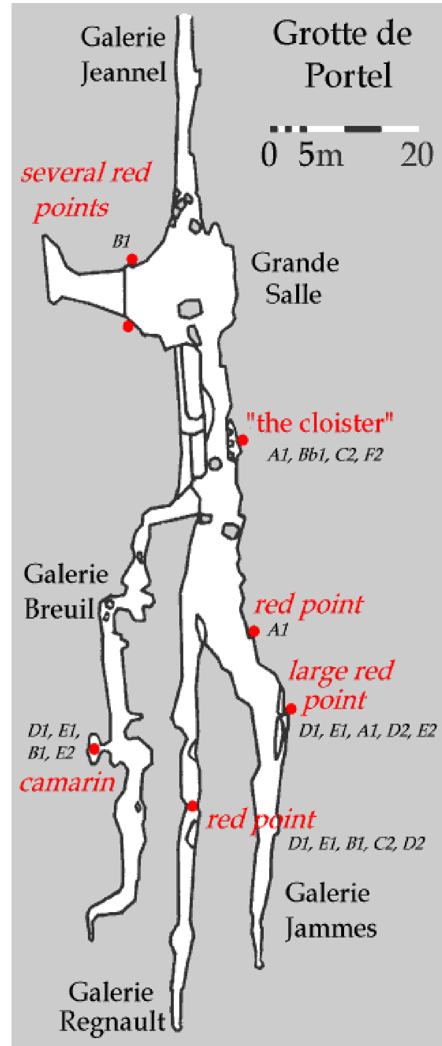
Acoustical resonance properties of this cave recently studied by Prof. Iegor Reznikoff & his University Paris/Nanterre research team.

Paeleolithic man would have explored caves by dull light of torches, and using his voice like sonar/echo-location to navigate around corners, avoid holes, explore nooks/crannies of the cave…

Reznikoff's team discovered that the red dots in this cave were *markers* of acoustic resonances – and were very often within ~ 1-2 meters of paintings in the cave.

Brought in trained vocalist to map out the acoustic resonances.

Also found by modulating harmonic content and amplitude, some resonances sounded very similar to the sounds made by the animals painted on nearby wall!!!



From the perspective of "survival of the fittest", <u>all</u> animals living on our planet are fundamentally / primarily interested in their own species, and secondarily in other species (e.g. as food/to keep from becoming food…)

We humans are *no* different in this regard. Our *anthropocentric* view of ourselves is also reflected in the structure of our music - e.g. consonant intervals, musical scales, etc. as well as in the musical instruments we have developed over the millennia.

It is absolutely *not* an accident that *many* of our musical instruments mimic the human voice – i.e. 1-D vibrating systems with integer-related harmonics {$f_n = nf_1$} for overtones – some musical instruments succeed in this more closely than others, which can be viewed as ~ artistic abstractions of the human voice. Skilled musicians playing such instruments can evoke in us strong emotions as if we were listening to a human in agony/pain, joy/ecstasy, sorrow, etc.

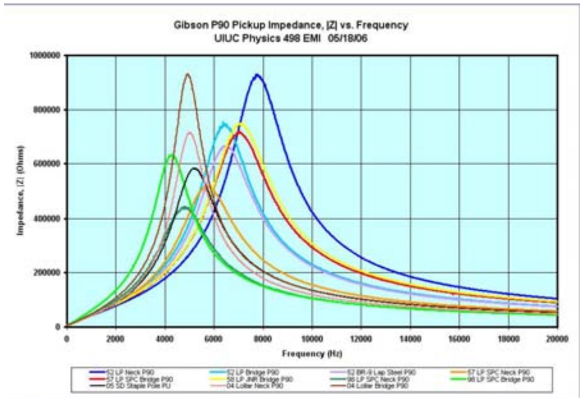
Similarly, it is also *not* an accident that {inharmonic $f_n \neq nf_1$} 2-D percussion instruments – drums etc. are used to mimic the impulsive sounds associated with internal human rhythms – e.g. our heart beat, blood pulsing through our veins, breathing, etc.

Both classes {1-D and 2-D} of musical instruments can also be/have been used in musically artistic ways to mimic the voices, etc. of animal species that are of secondary interest to us – e.g. the singing of birds, the roar of lions, howling of wolves, the clip-clop of horses hooves, etc.

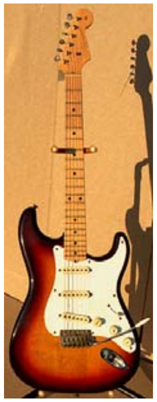
A Test of My Own Long-Term Musical Memories:

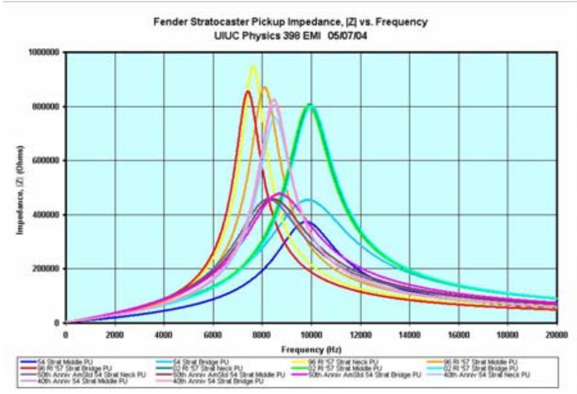
I played {electric} guitar in the mid-60’s – mid-70’s; started playing again in ~ mid-90’s: “Faithful” modern-day re-issues of vintage guitars *didn’t* sound like the real deal to *my* ears... Due to false memories, or actual truth??? I explicitly checked:

Gibson P-90’s in Les Pauls, Les Paul Jr, …

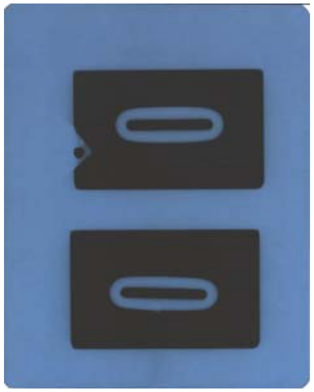


Fender Stratocaster Pickups

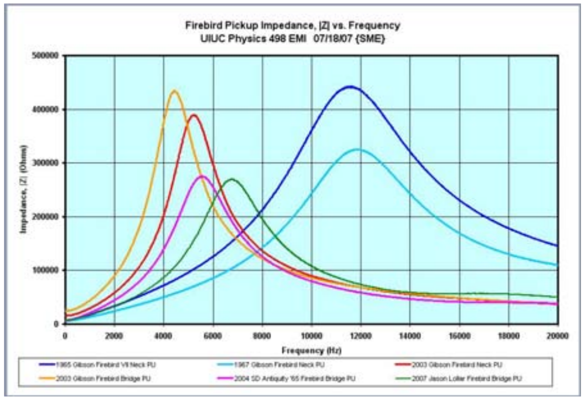




X-ray of P-90 PUs from ’52 (top) vs. ’98 RI (bottom) Gibson Les Paul Guitars:



Gibson Firebird Pickups



<u>Some Closing Comments</u>:

<u>Nature vs. Nurture</u>: Infants & young children (< 8 yrs) undergo enormous development in their brains – literally wiring the connections in their brains in a myriad of ways. Children deprived of sight/vision for any significant length of time (e.g. due to eye infection) are at risk of life-long adverse impact because of this. Presume similar/analogous adverse effect(s) will occur if children grow up in environment completely *devoid* of all music – those brain areas not used for processing of music will be wired for other uses… Would we eventually lose our musical roots? {n.b. We've lost the ability to internally produce vitamin C because of eating fruit in our diet – still internally produce other vitamins, e.g. vitamin D, etc. Our appendix is also a legacy-organ…}

$\Rightarrow$ Importance of music in fostering development of our children, and *<u>synergy</u>* in their education! {n.b. I have quiet consciously/deliberately utilized/relied on/capitalized on the intrinsic human interest/enjoyment/ pleasure in music – using it to get students *excited* about acoustical physics {& science in general} in teaching the physics of music/musical instruments courses at UIUC – it *<u>really</u>* works, amazingly well !!!}

<u>Information Overload</u>: What is the impact – *short* and *long-term* – on us humans (and other creatures) living in the modern-day world, filling our heads 24/7 with overdoses of information & sounds coming at us seemingly from all directions, and at an ever-increasing pace? Think about this in terms of our biological origins… will our heads explode at some point???

The development of new technologies {e.g. fMRI, DNA sequencing, …} in multiple areas of research has led to many exciting discoveries in the past few years, in terms of us gaining a better understanding of the importance of music in our daily lives in the here-and-now, and how this all came about – i.e. our past – *Did* music play an important evolutionary role in our development???

The current picture on this topic is *<u>far</u>* from complete… However, more and more people appear to be getting involved & investigating as more becomes known – the pace is accelerating…. The nature of this subject is such that it requires/would benefit greatly from multi-disciplinary research/collaboration…

***If* intelligent life does exist elsewhere in the universe, would such beings *also* have music in their culture? *If* so, did music also play an important role in their evolution? What would *their* music sound like? Would their musical instruments mimic their own voices, their own internal rhythms?**

Many, many things to think about, investigate & study!

We live in *<u>very</u>* exciting times in this regard {as well as in *<u>many</u>* others}!

If Interested: Suggested/Recommended Books for Further Reading:

- "*This is Your Brain on Music – The Science of Human Obsession*", Daniel Levitin, Dutton, 2006.
- "*The World in Six Songs*", Daniel Levitin, Dutton, 2008.
- "*The Singing Neanderthals – The Origins of Music, Language, Mind and Body*", Steven Mithen, Harvard University Press, 2007.
- "*The Origins of Music*", Nils Lennart Wallin, Björn Merker, Steven Brown, MIT Press, 2001.
- "*Musicophilia – Tales of Music and the Brain*", Oliver Sachs, Alfred A. Knopf, Inc., 2007.

Website(s) for UIUC Physics of Music/Musical Instruments Courses (if interested):
Freshman "Discovery" Course: http://online.physics.uiuc.edu/courses/phys199pom/
Upper-Level Undergrad Physics Course: http://online.physics.uiuc.edu/courses/phys498pom/

n.b. **Copies of *this* and other POM talks available at either of these two websites – see "POM Talks"**

The Jimi Hendrix Experience:

Noel Reading, Jimi Hendrix, Mitch Mitchell

3rd Stone from the Sun

"Are You Experienced" Album

Track Records/Polydor Records, 1967

3rd Stone from the Sun

Starfleet to scoutship, please give your position, Over.
I'm in orbit around the third planet from the star called
The sun. Over.
You mean it's the earth? Over.
Positive. It is known to have some form of intelligent
Species. Over.
I think we should take a look.

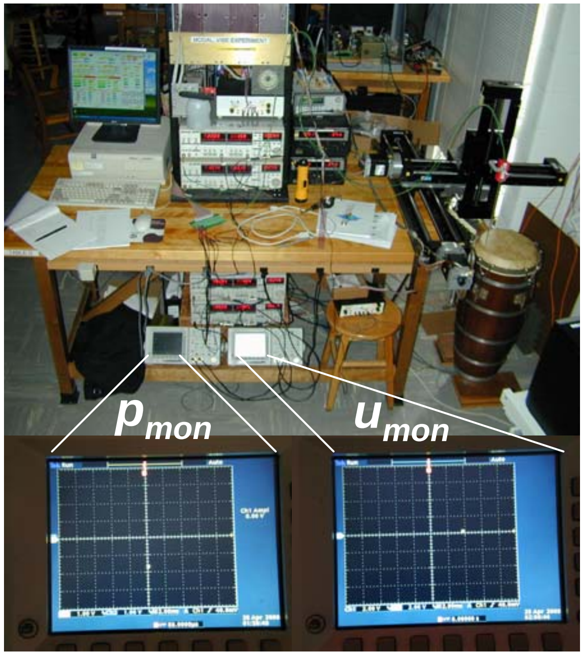
Strange beautiful grass of green,
With your majestic silver seas
Your mysterious mountains I wish to see closer
May I land my Tiki machine

Strange beautiful grass of green,
With your majestic silver seas
Your mysterious mountains I wish to see closer
May I land my Tiki machine

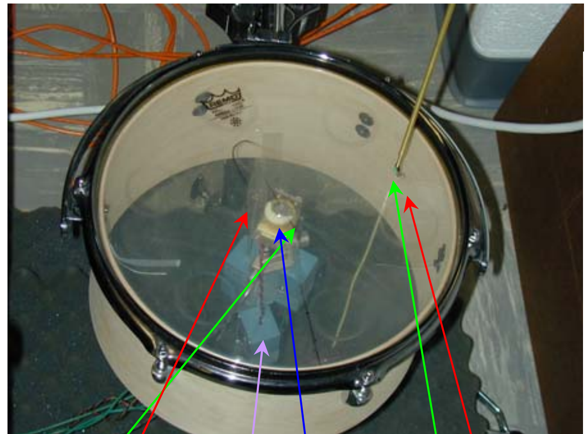
Although your world wonders me,
With your majestic and superior cackling hen
Your people I do not understand,
So to you I shall put an end
And you'll
Never hear
Surf music again

Secret
Oh, secret
Oh
Shhhh...

UIUC P498POM Modal Vibes DAQ Experiment: *Phase-Sensitive* Acoustic Holography!



p-complex plane *u*-complex plane

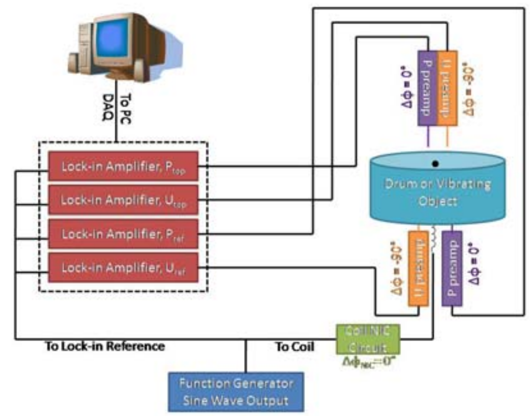


p, u monitor mics

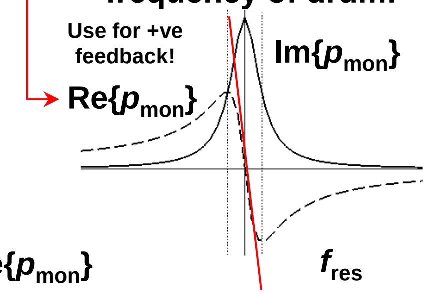
CC NIC + coil driver + rare-earth magnet pair

p, u scan mics

Block Diagram of Modal_Vibes DAQ System:



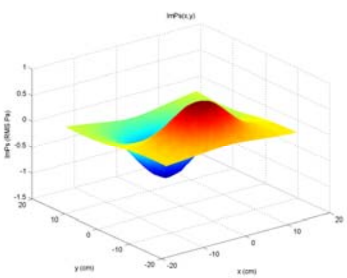
Mode-lock to resonant frequency of drum:



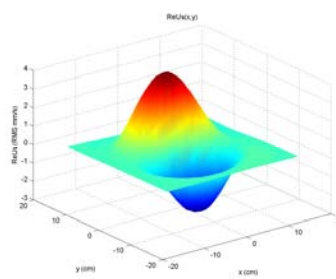
Doumbek:

J_{11} Vibrational Mode of Doumbek:
(32x32 = 1024 scan points, 1 cm step size)

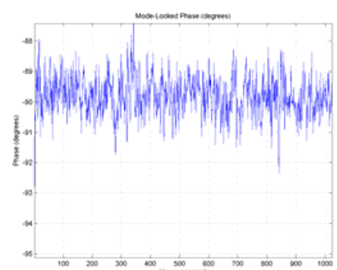
Im{*p*(x,y)}



Re{*u*(x,y)}



Phase{p_{mon}}



Drums *very* sensitive to temperature changes!