Piano ✵ Repair & Tuning

For Physicists & Engineers

using your

Laptop, Microphone, and Hammer

by

Bruce Vogelaar, Hans Robinson, Tatsu Takeuchi

Virginia Tech

at

3:00 - 4:30 pm Hahn Hall North Rm 130

April 20, 2019

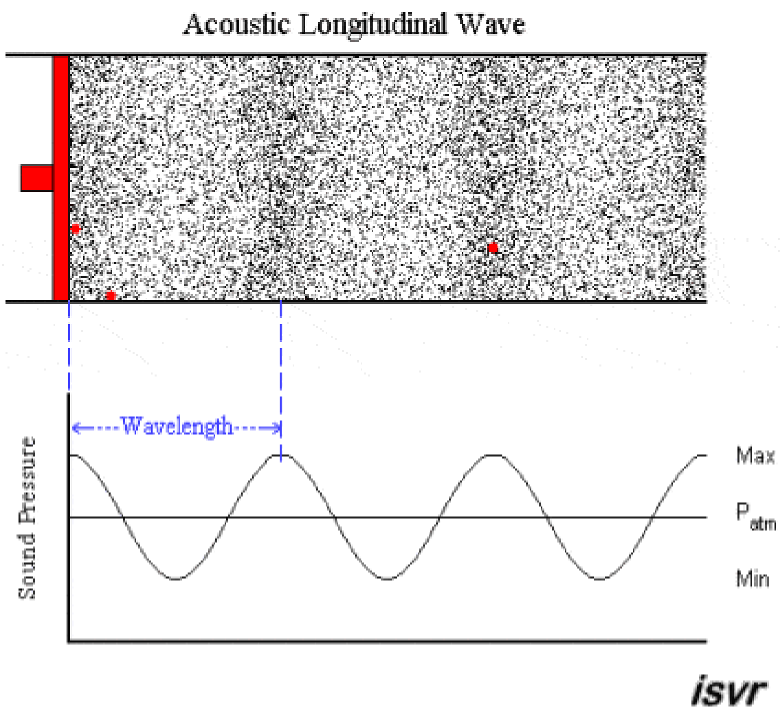
24 tone fun

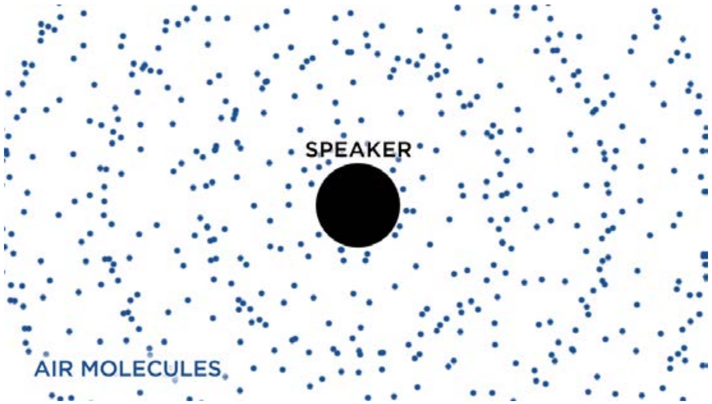
Janko Keyboard

Fluid piano

Piano Tuning

A pure sound pitch is a pressure wave travelling in air at speed v, with frequency f, and wavelength λ.



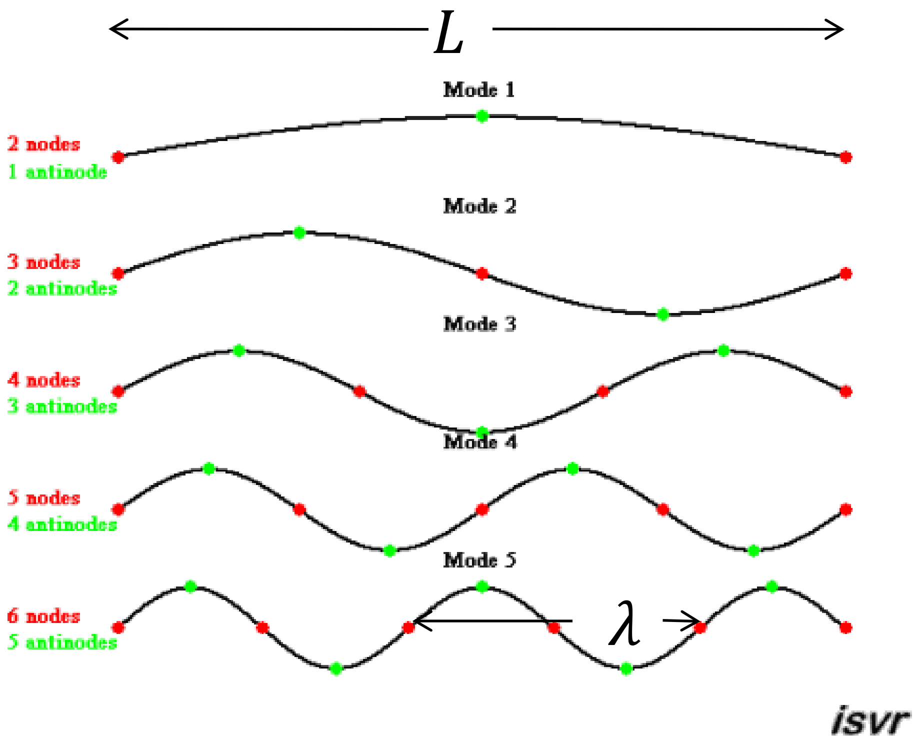


note: any given gas molecule just goes back and forth.

$$f\lambda = v$$

String instruments vibrate at specific frequencies:

A piano string is fixed at its two ends, and can vibrate in several harmonic modes.



$$L = n\frac{\lambda}{2};$$

$$f_n = \frac{v}{\lambda} = n\frac{v}{2L} = nf_0$$

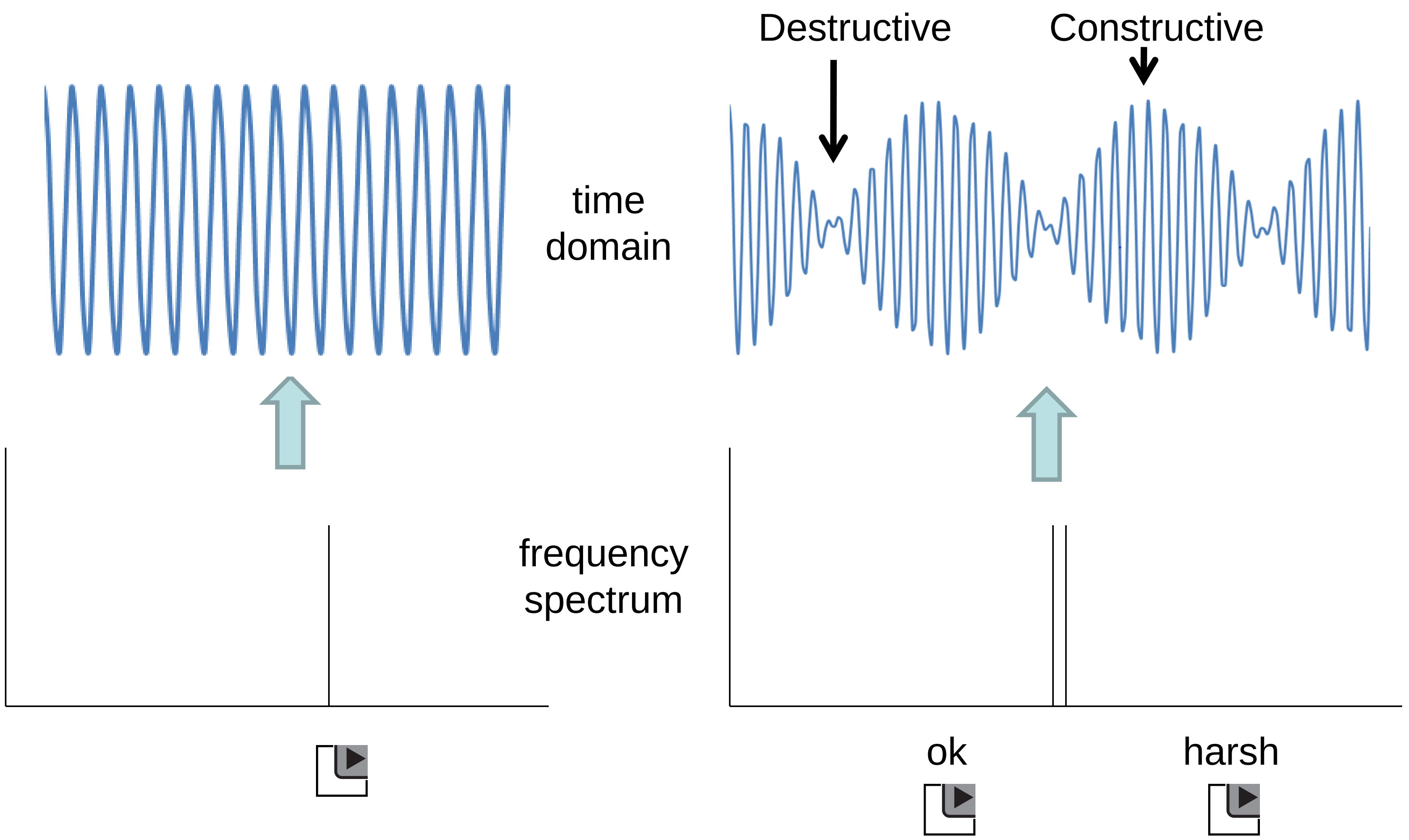
$$\omega_n = 2\pi f_n$$

[***v*** = speed of wave ***on string***]

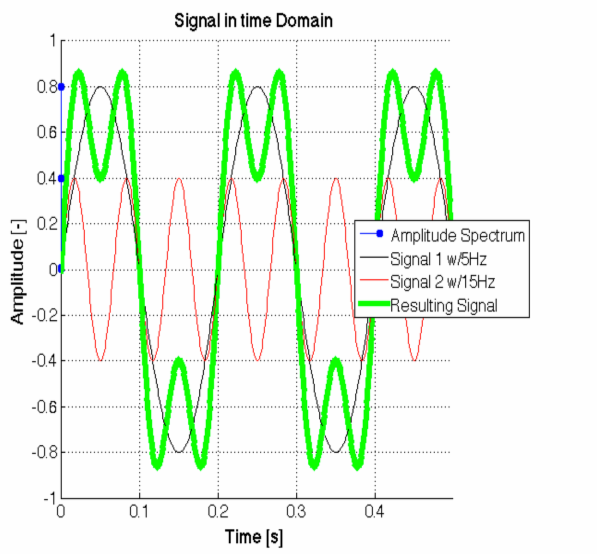
Converting string motion into sound is difficult:

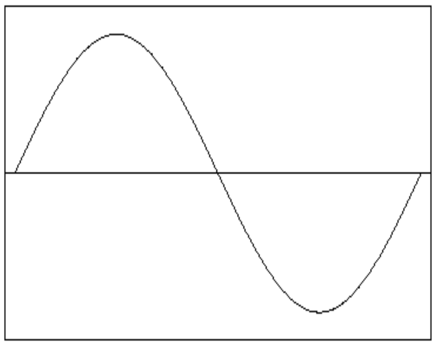
- sound board
- resonant cavity
- electric pickups to amp to speaker

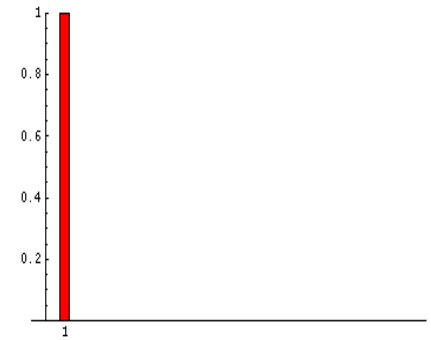
Add sounds together:



Add sounds together:







frequency content determines ‘timbre’

Invert: given the ‘sum’,

what were the components?

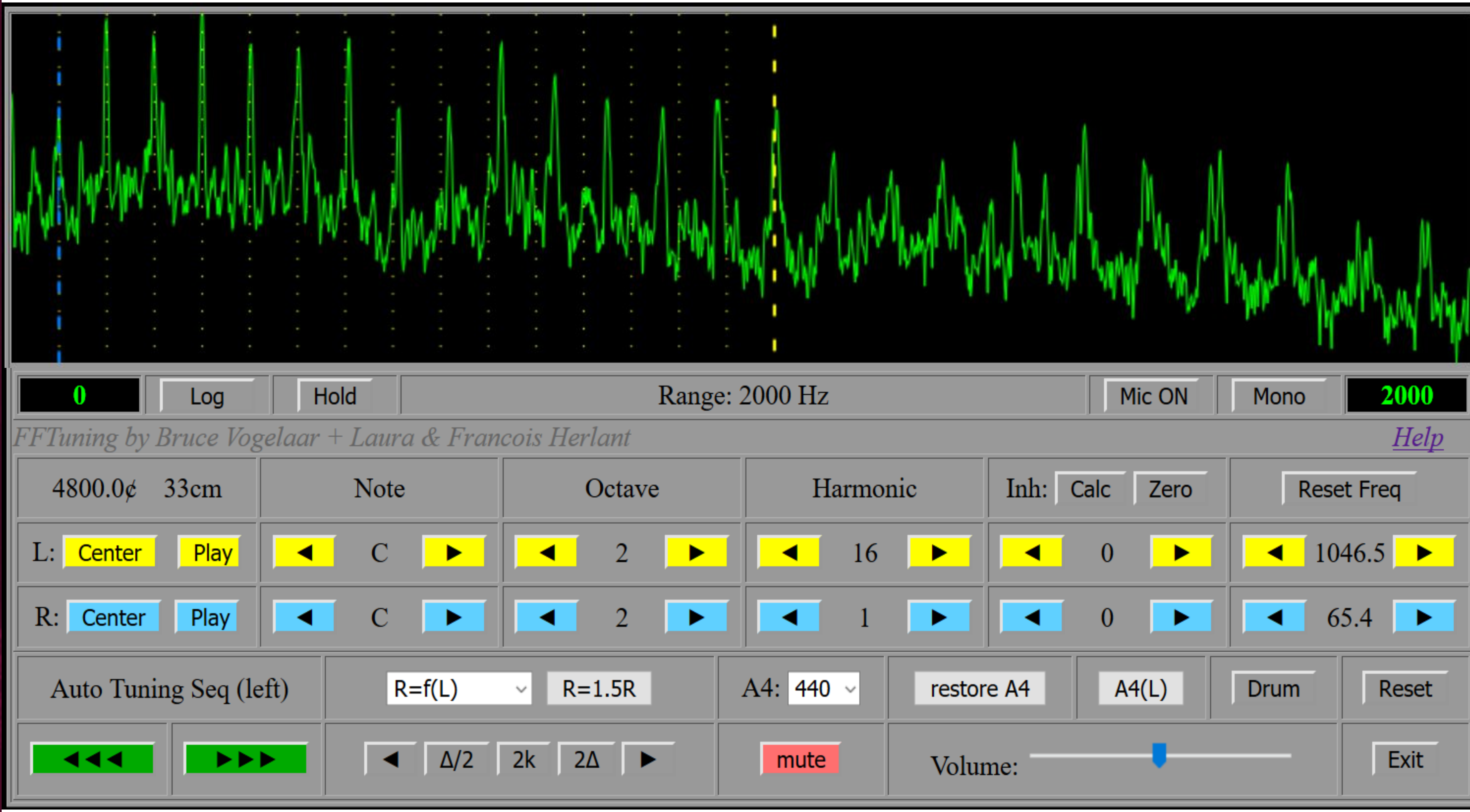
Fast Fourier Analysis as in FFTuner @

www.phys.vt.edu/~vogelaar

please read the Help file which covers everything here in more detail

https://www1.phys.vt.edu/~kimballton/home/pub/piano/tuner-app/FFTuning.htm

C2 struck with key; log scale makes everything easier to see



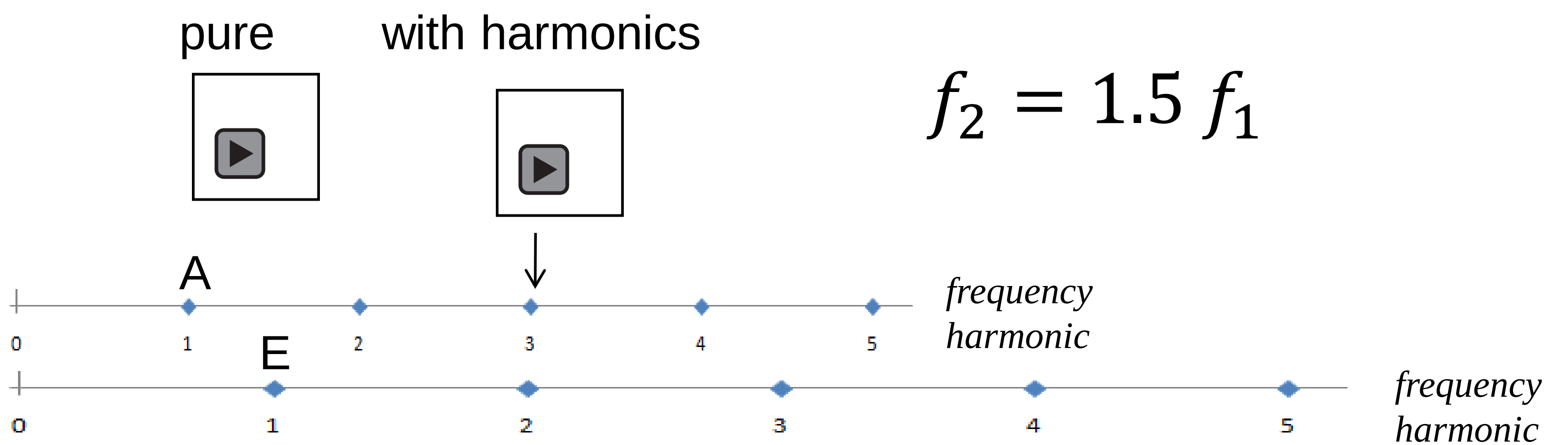
You might want a powered base microphone for the low frequencies.

Why some notes sound ‘harmonious’ together

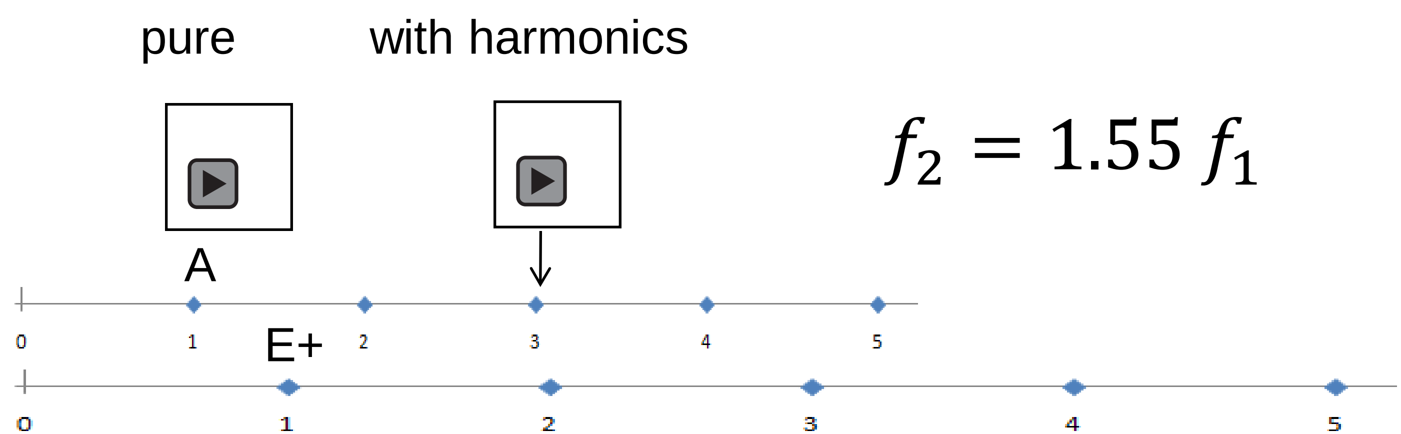
or rather, which notes don’t sound terrible together….

their harmonics are either matched or well separated

(In practice, you can hardly ever avoid harmonics of a fundamental.)

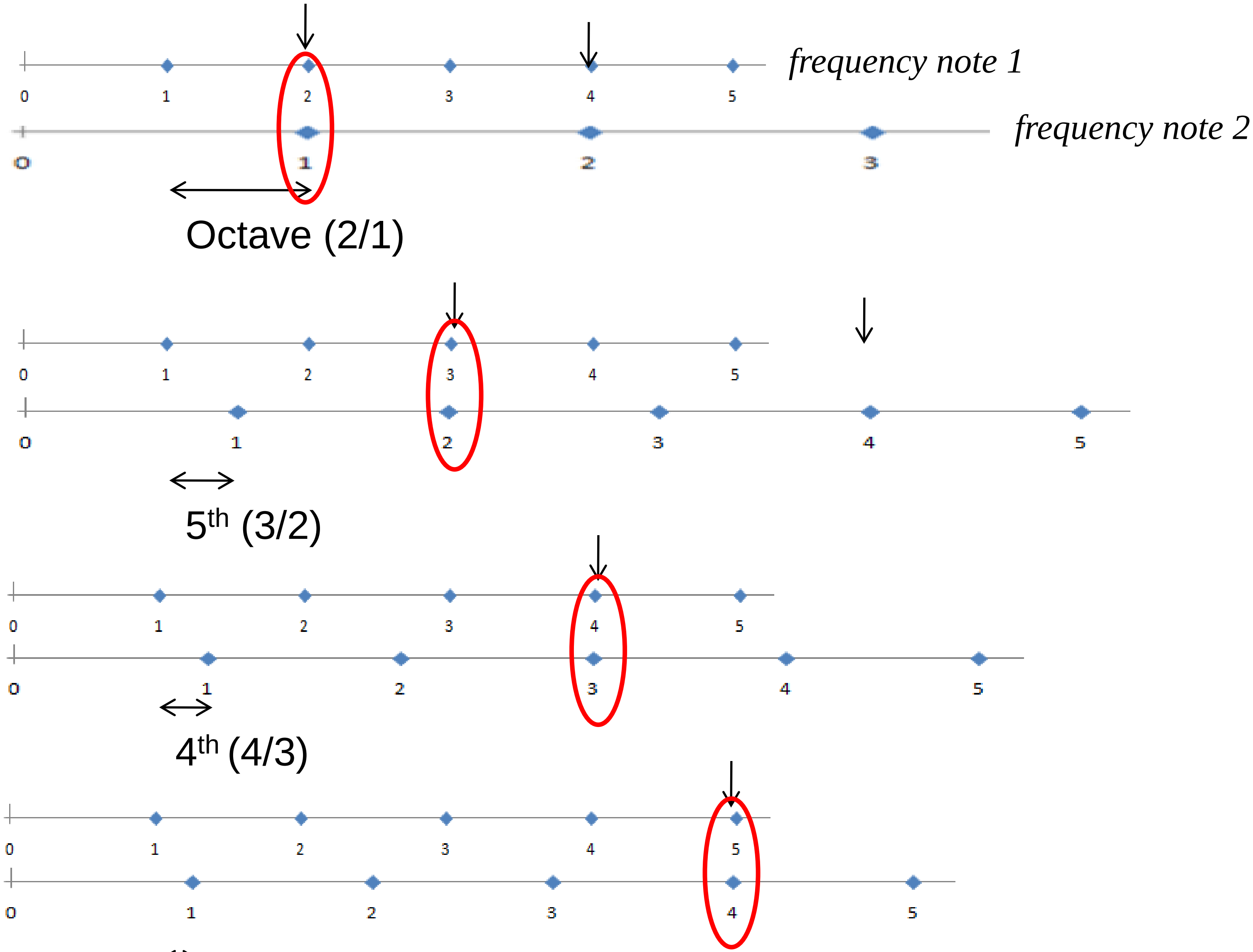


$$f_2 = 1.5\ f_1$$



$$f_2 = 1.55\ f_1$$

Origins of the Just Temperament



3^{rd} (5/4)

Octaves are universally pleasing; to the Western ear, the 5^{th} is next most important.

"Circle of 5th s"

Going up by 5ths
12 times brings you ***very***
near the same note
(but 7 octaves up)

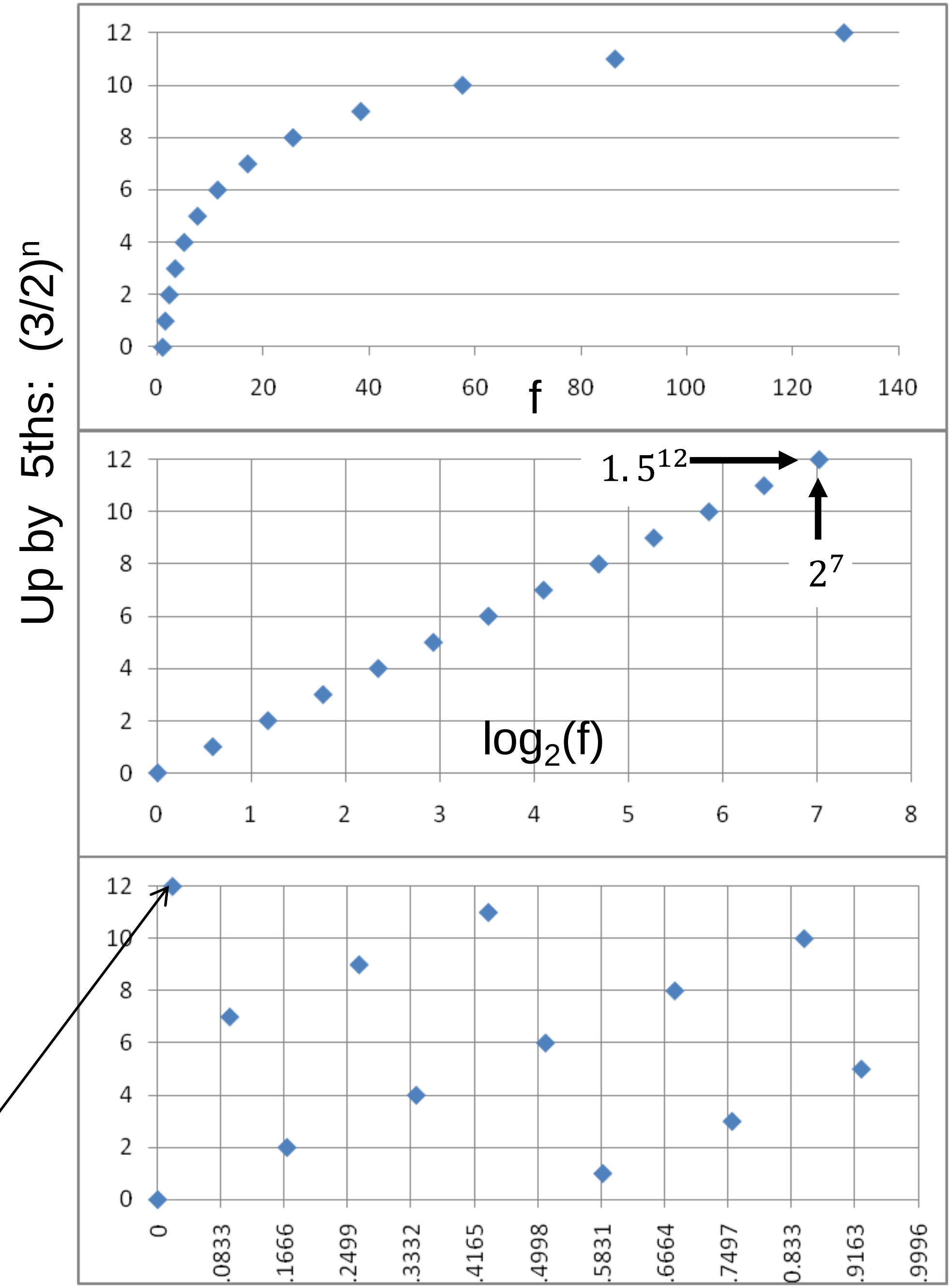
this suggests 12 notes per octave

Equal temper: space by $\sqrt[12]{2}$

'cents' between two notes:
$1200 * \log_2(f_2/f_1)$

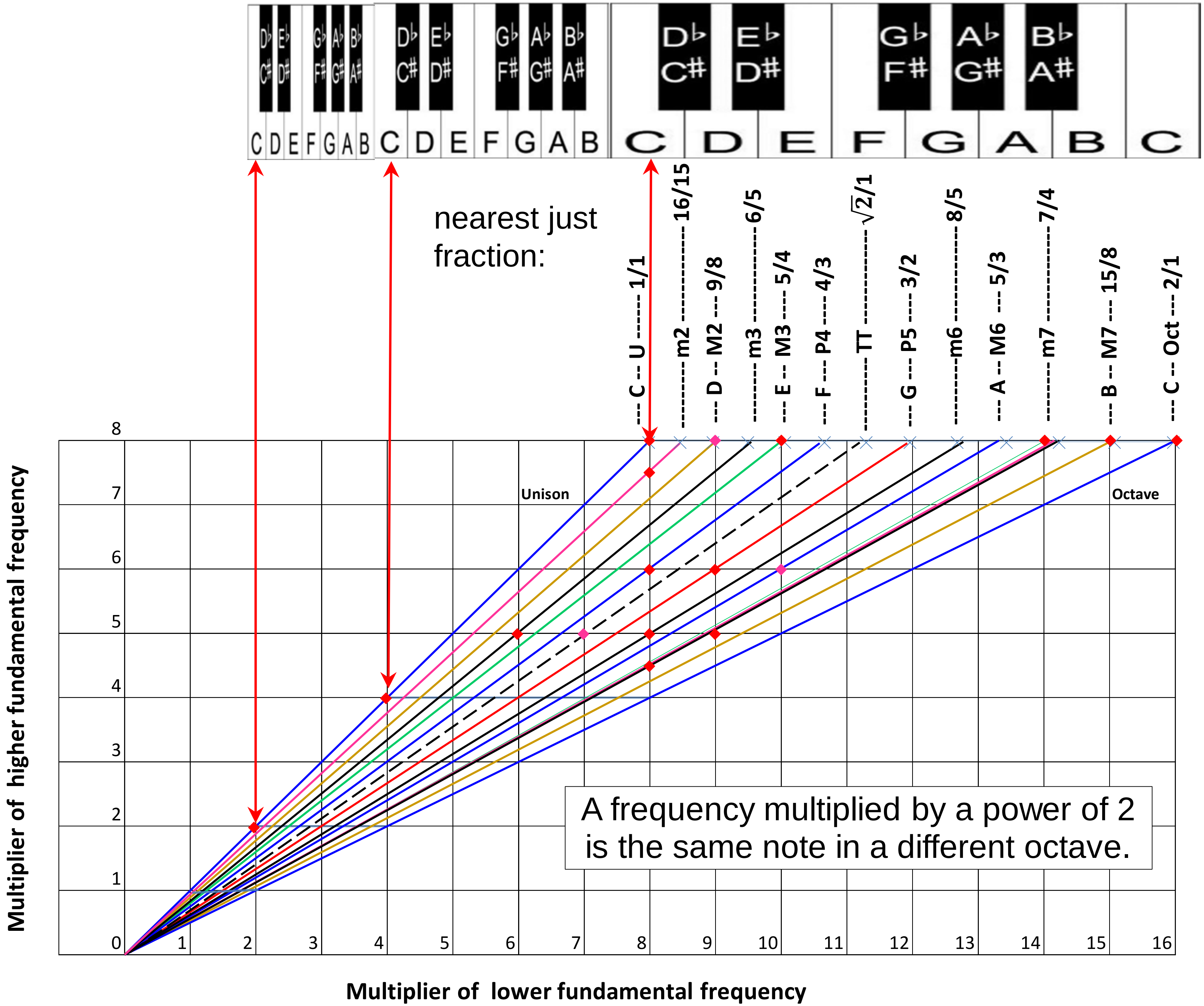
Octave = 1200 cents
("Wolf " fifth is off by 23 cents.)

"Wolf " fifth



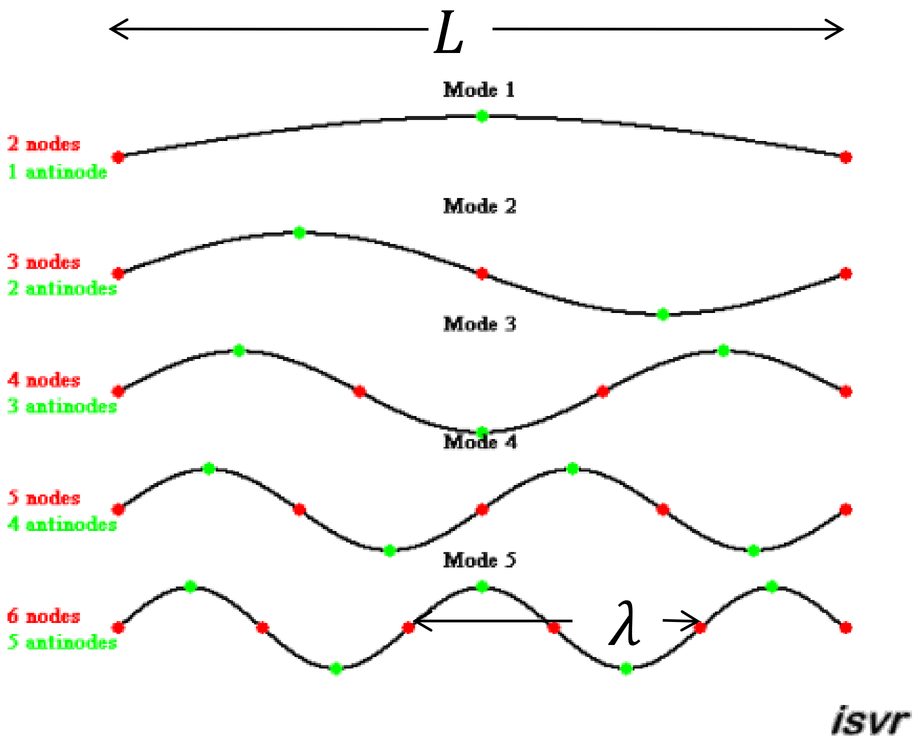
$\log_2(f)$ shifted down into same octave

Piano Tuning



Guitar

A guitar string is fixed at its two ends, and can vibrate in several harmonic modes.



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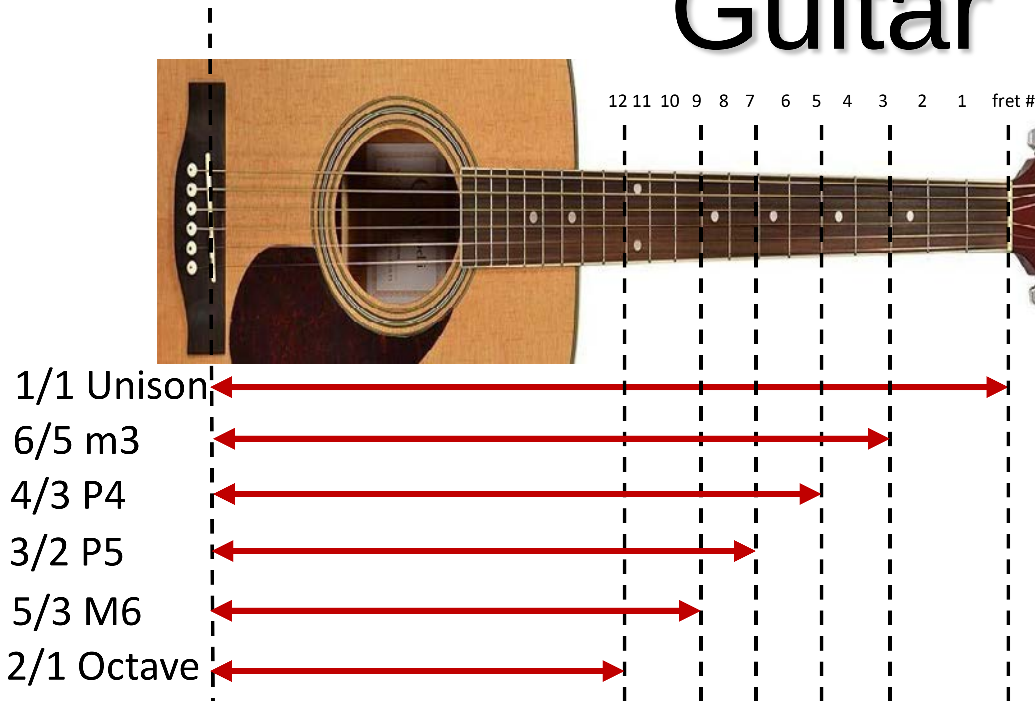
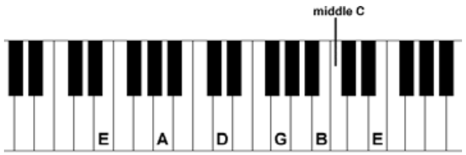
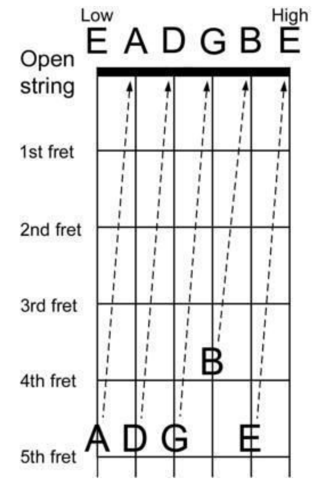
Guitar





String	Note	Frequency
6	E 2	82.4
5	A 2	110.0
4	D 3	146.8
3	G 3	196.0
2	B 3	246.9
1	E 4	329.6

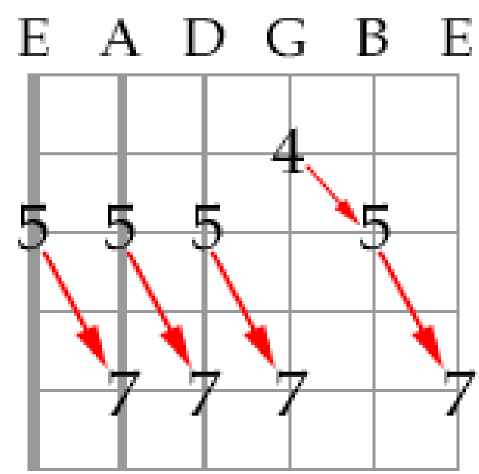


Spacing between frets:

$$\frac{f_{n+1}}{f_n} = \frac{L_n}{L_n - x} = \sqrt[12]{2}$$

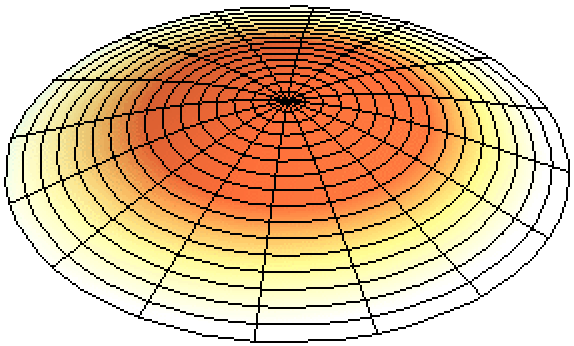
$$x = \left(1 - 2^{-1/12}\right)L_n = 0.05613L_n$$

Pressing a string between frets raises the tension in the string leading to the idea of harmonic tuning:

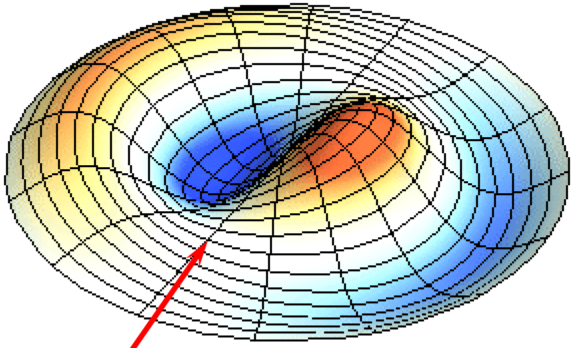


Play harmonics by lightly touching strings when strumming at 1/2, 1/3, 1/4 length, etc.

Drums



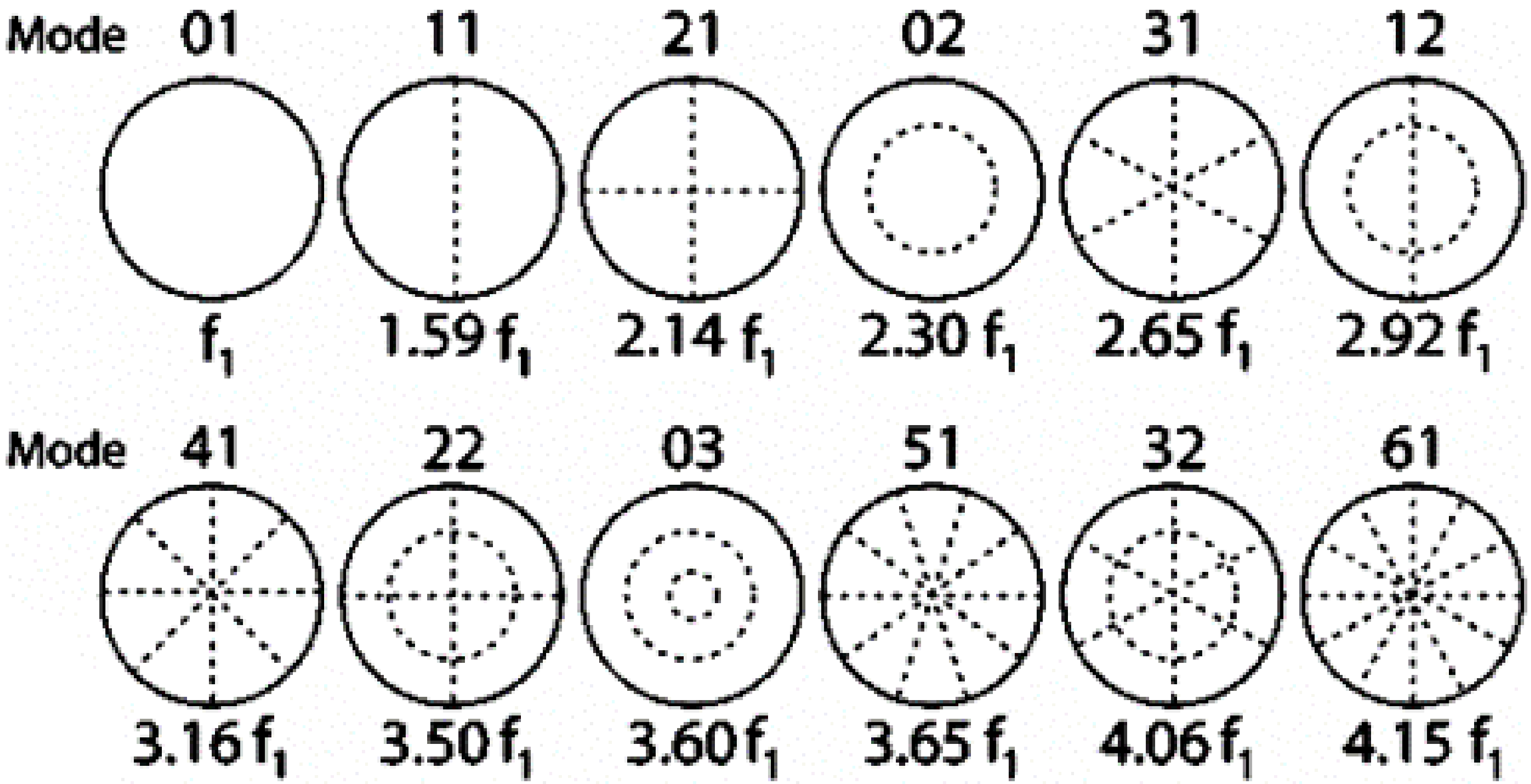
(0,1)



(1,2)

radial and azimuthal nodes

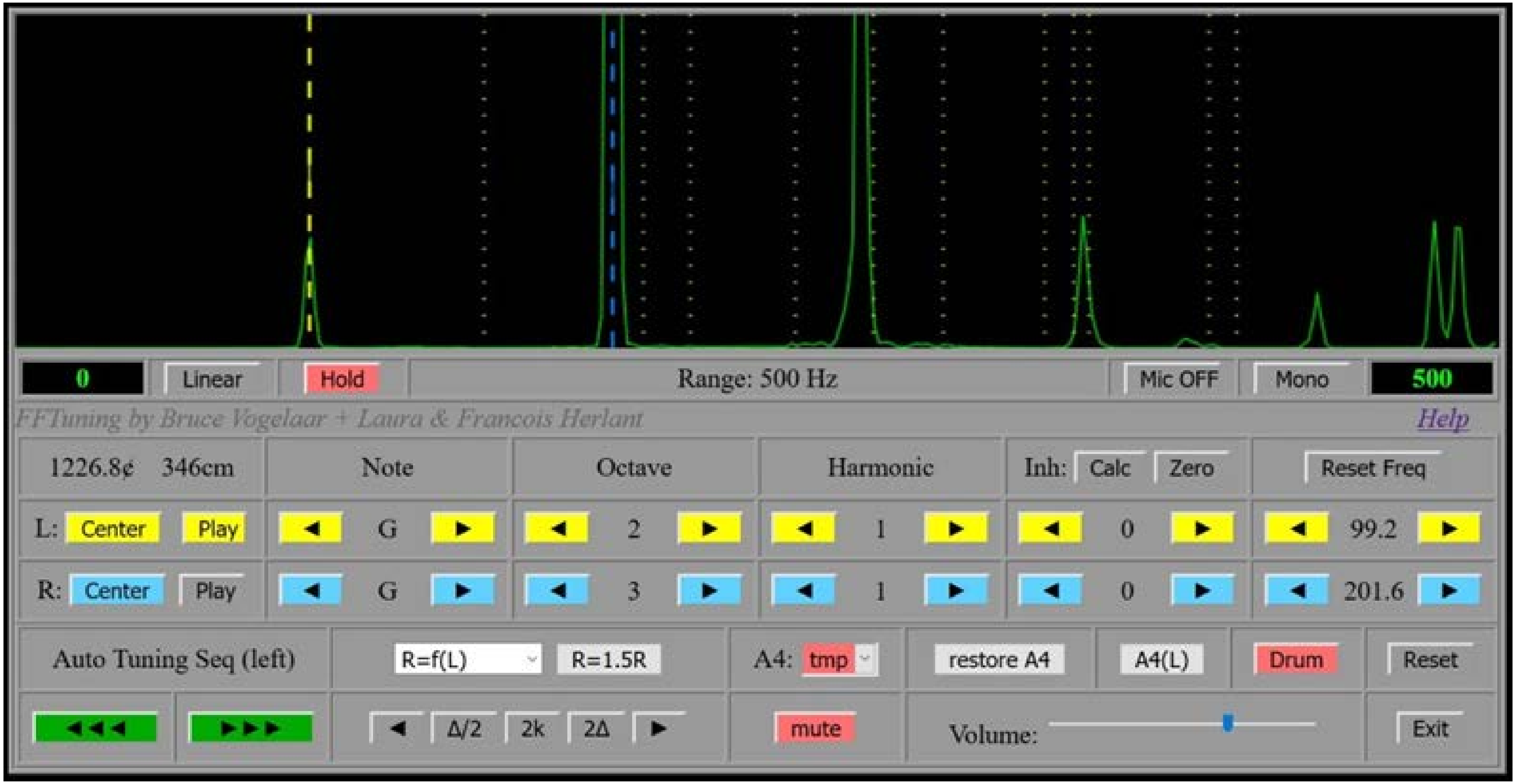
Drums



Modes of an ideal drumhead in a vacuum.

This is NOT what you'll see on a real drum.

Drums

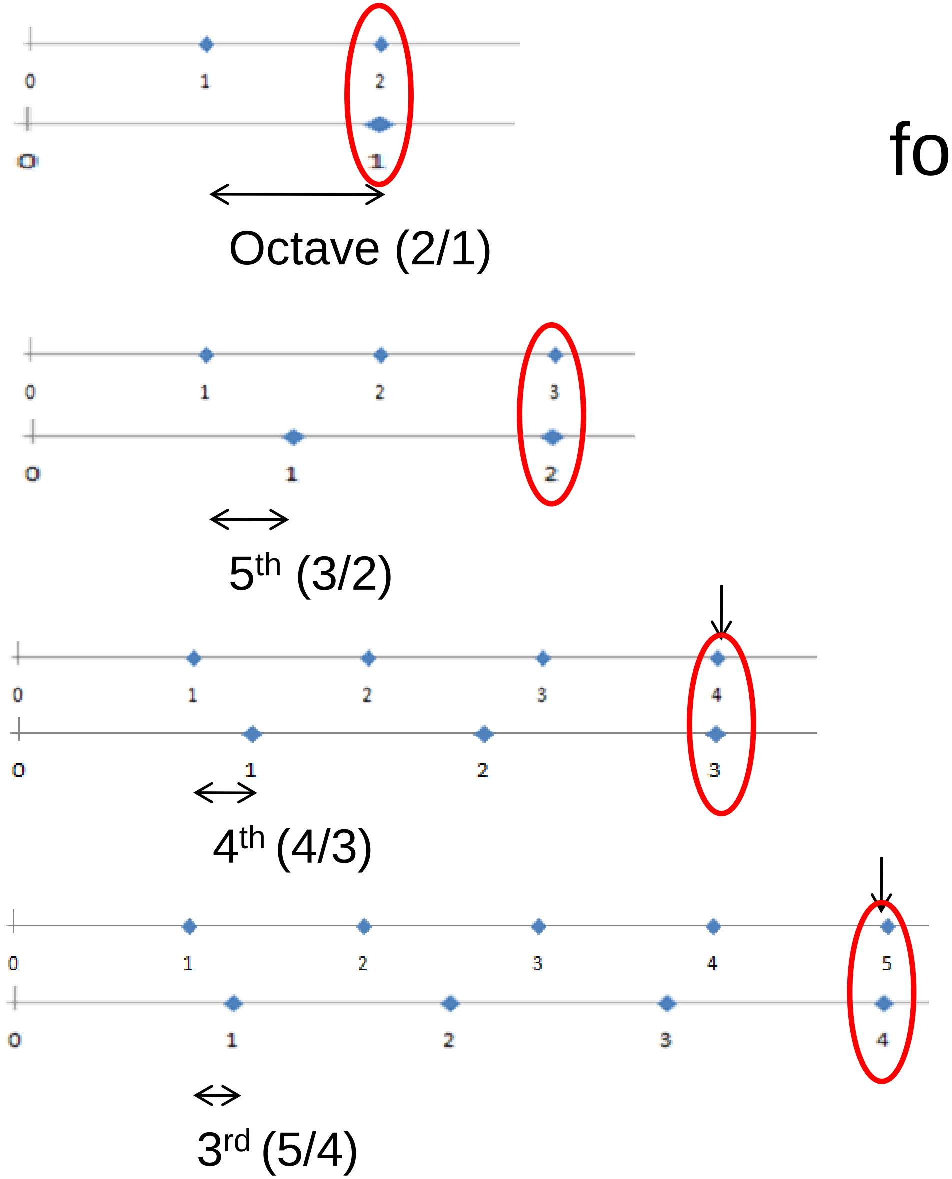


First three are (0,1), (1,1), and (2,1).

Can confirm this by dampening out other modes (like playing harmonics on a guitar)

Piano Tuning

Back to pianos: what an 'aural' piano tuner does…



for ***equal*** temperament:

tune so that desired harmonics are at the same frequency;

then, set them the required amount off by counting 'beats'.

Piano Tuning

Piano Tuning

Equal temperament beatings (all figures in Hz)												
261.626	277.183	293.665	311.127	329.628	349.228	369.994	391.995	415.305	440.000	466.164	493.883	523.251
0.00000			14.1185	20.7648	1.18243		1.77165	16.4810	23.7444			C
		13.3261	19.5994	1.11607		1.67221	15.5560	22.4117			B	
	12.5781	18.4993	1.05343		1.57836	14.6829	21.1538			B♭		
11.8722	17.4610	.994304		1.48977	13.8588	19.9665			A			
16.4810	.938498		1.40616	13.0810	18.8459			A♭				
.885824		1.32724	12.3468	17.7882			G				Fundamental	
	1.25274	11.6539	16.7898			F♯					Octave	
1.18243	10.9998	15.8475			F						Major sixth	
10.3824	14.9580			E							Minor sixth	
14.1185			E♭								Perfect fifth	
		D									Perfect fourth	
	C♯										Major third	
C											Minor third	

Perfect Fifth: from C, set G above it such that an octave and a fifth above the C you hear a 0.89 Hz 'beating'

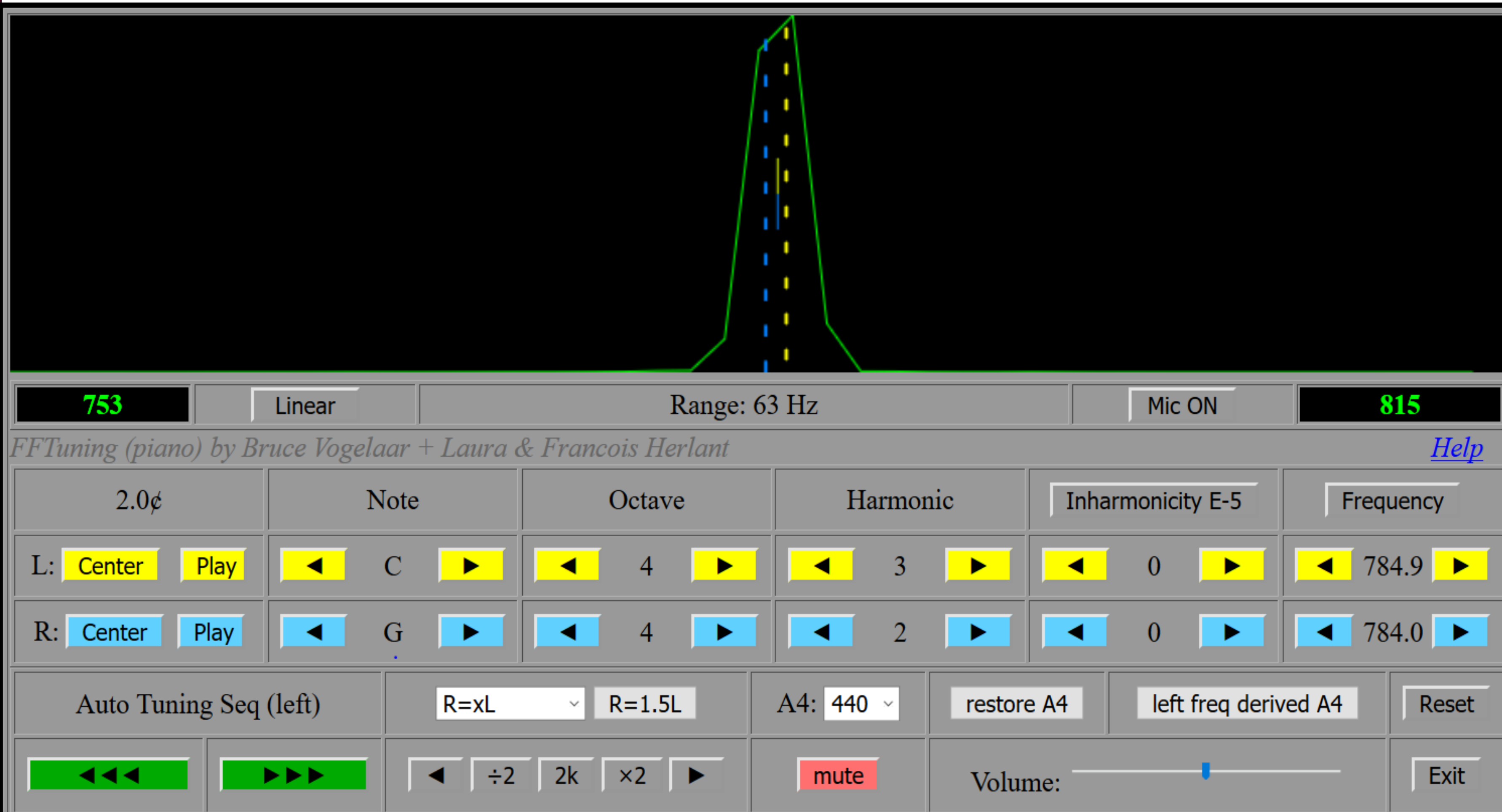
Interval	Approximate ratio	Beating above the lower pitch	Tempering
Unison	1:1	Unison	Exact
Octave	2:1	Octave	Exact
Major sixth	5:3	Two octaves and major third	Wide
Minor sixth	8:5	Three octaves	Narrow
Perfect fifth	3:2	Octave and fifth	Slightly narrow
Perfect fourth	4:3	Two octaves	Slightly wide
Major third	5:4	Two octaves and major third	Wide
Minor third	6:5	Two octaves and fifth	Narrow

I was hopeless, and even wrote a synthesizer to try and train myself…

but I still couldn't 'hear' it…

These beat frequencies are for the central octave.

Perfect Fifth: the 2 cent beat frequency is easy to hear, when isolated.



Is it hopeless?

not with a little help from math
and a laptop…

we (non-musicians) can use a
spectrum analyzer…

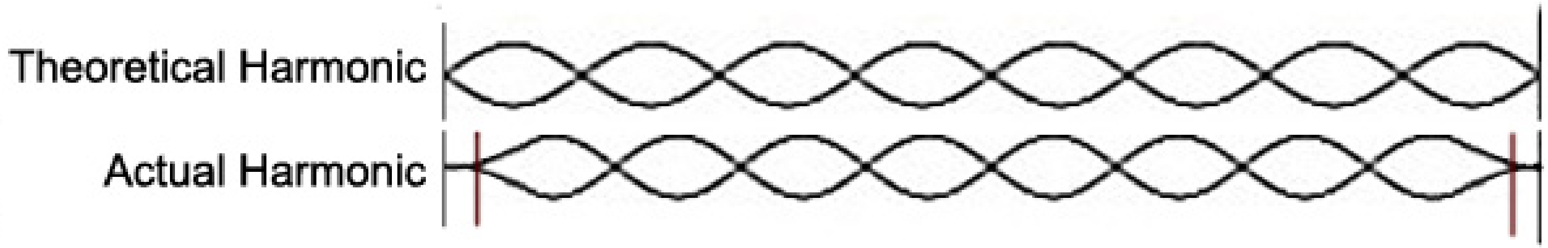
With a (free) “Fourier” spectrum analyzer we can set the pitches exactly!

True Equal Temperament Frequencies

	0	1	2	3	4	5	6	7	8
C		32.70	65.41	130.81	261.63	523.25	1046.50	2093.00	4186.01
C#		34.65	69.30	138.59	277.18	554.37	1108.73	2217.46	
D		36.71	73.42	146.83	293.66	587.33	1174.66	2349.32	
D#		38.89	77.78	155.56	311.13	622.25	1244.51	2489.02	
E		41.20	82.41	164.81	329.63	659.26	1318.51	2637.02	
F		43.65	87.31	174.61	349.23	698.46	1396.91	2793.83	
F#		46.25	92.50	185.00	369.99	739.99	1479.98	2959.96	
G		49.00	98.00	196.00	392.00	783.99	1567.98	3135.96	
G#		51.91	103.83	207.65	415.30	830.61	1661.22	3322.44	
A	27.50	55.00	110.00	220.00	440.00	880.00	1760.00	3520.00	
A#	29.14	58.27	116.54	233.08	466.16	932.33	1864.66	3729.31	
B	30.87	61.74	123.47	246.94	493.88	987.77	1975.53	3951.07	

But first – a critical note about 'real' strings (where 'art' can't be avoided)

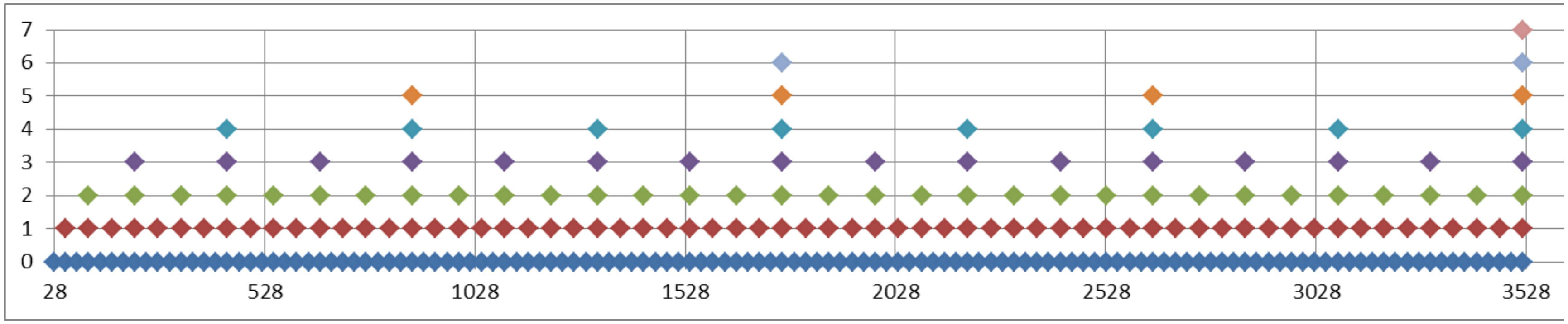
- strings have 'stiffness'
- bass strings are wound to reduce this, but not all the way to their ends
- treble strings are very short and 'stiff'
- thus harmonics are not true multiples of fundamentals



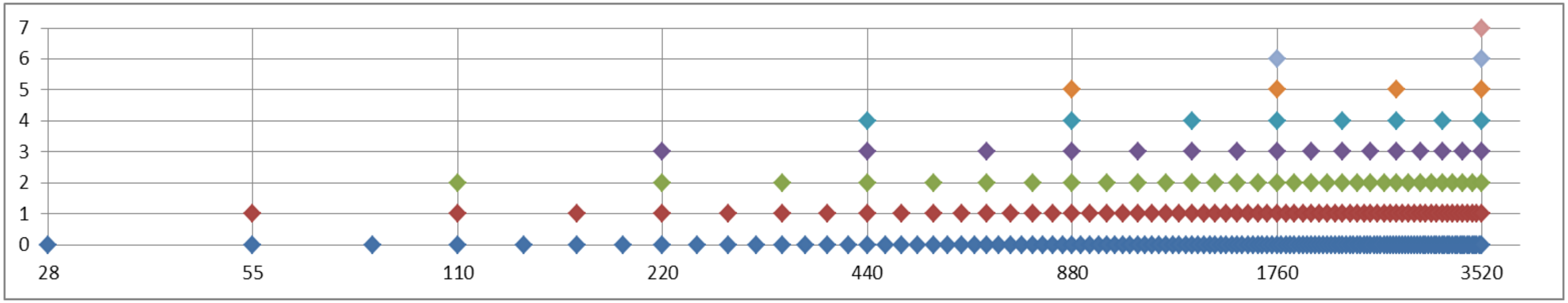
f_n is increased by a factor of $\sqrt{1 + \beta n^2}$

A4 (440) inharmonicity

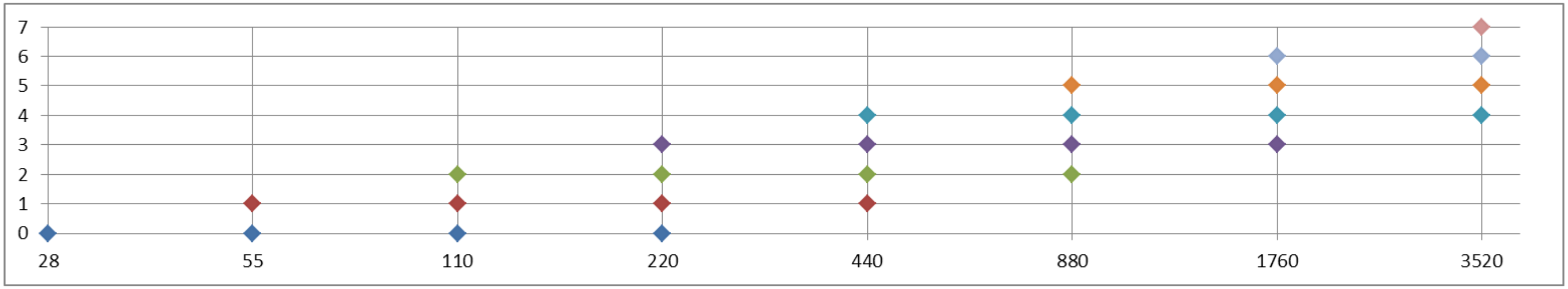
Tuning the 'A' keys: Ideal strings $f_0 = 440(2^n); n = -4 \cdots 2$



All the harmonics



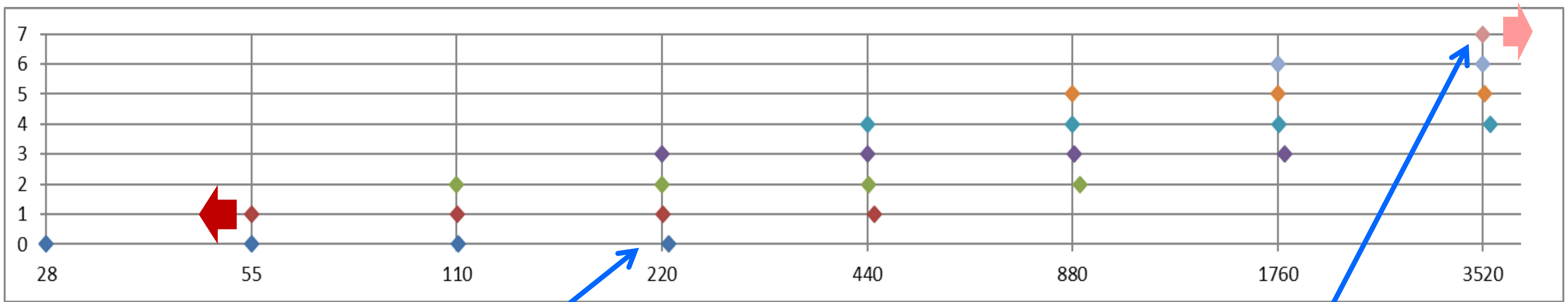
On a log scale



Only the nearby octaves

Piano Tuning

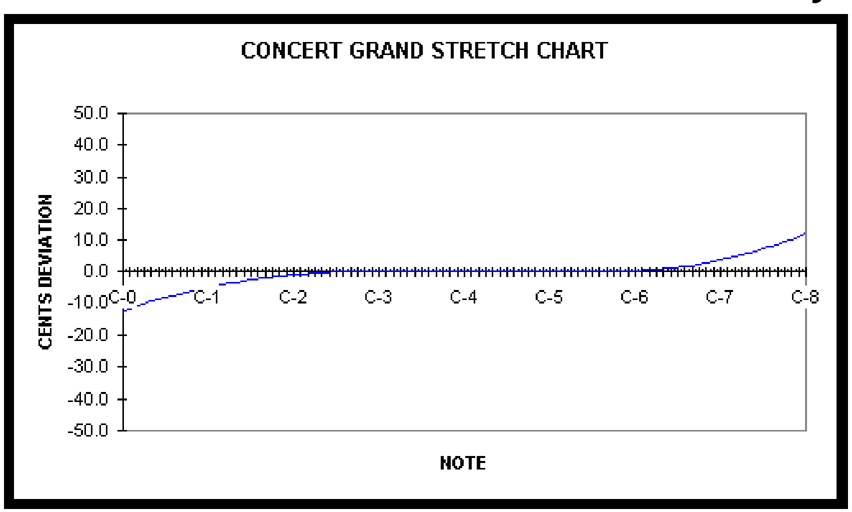
With 0.001 inharmonicity

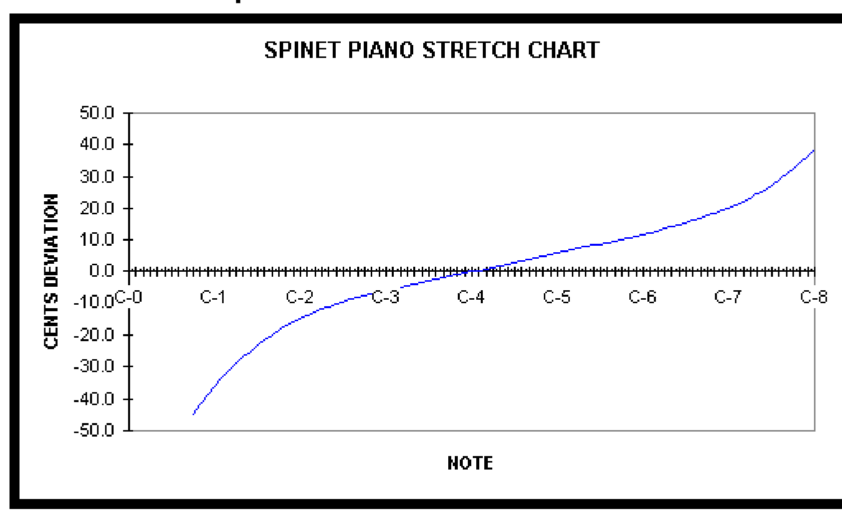


sounds 'sharp' sounds 'flat'

7															0.0
6													0.0		0.9
5											0.0		0.9		7.8
4									0.0		0.9		7.8		41.4
3							0.0		0.9		7.8		41.4		
2					0.0		0.9		7.8		41.4				
1			0.0		0.9		7.8		41.4						
0	0.0		0.9		7.8		41.4								

How many cents from perfect.





Need to "Stretch" the tuning. Can not match all harmonics, must compromise → 'art'

the FFTuner approach

Pluck/strike one string at a time

Tune octaves 3, 4, and 5 to their exact frequencies (setting the ‘temper’ and eliminating ‘stretch’ for this region as a reasonable first estimate).

For octaves 0, 1, and 2, tune their 8th, 4th, and 2nd harmonics respectively to match the same note in octave 3.

For octaves 6 and 7, tune their fundamentals to match the 2nd and 4th harmonics respectively from octave 5.

FFTuner pre-populates these choices to expedite the process. See Help file for lots of explanation.

tools of the trade…

! but some keys don't work !

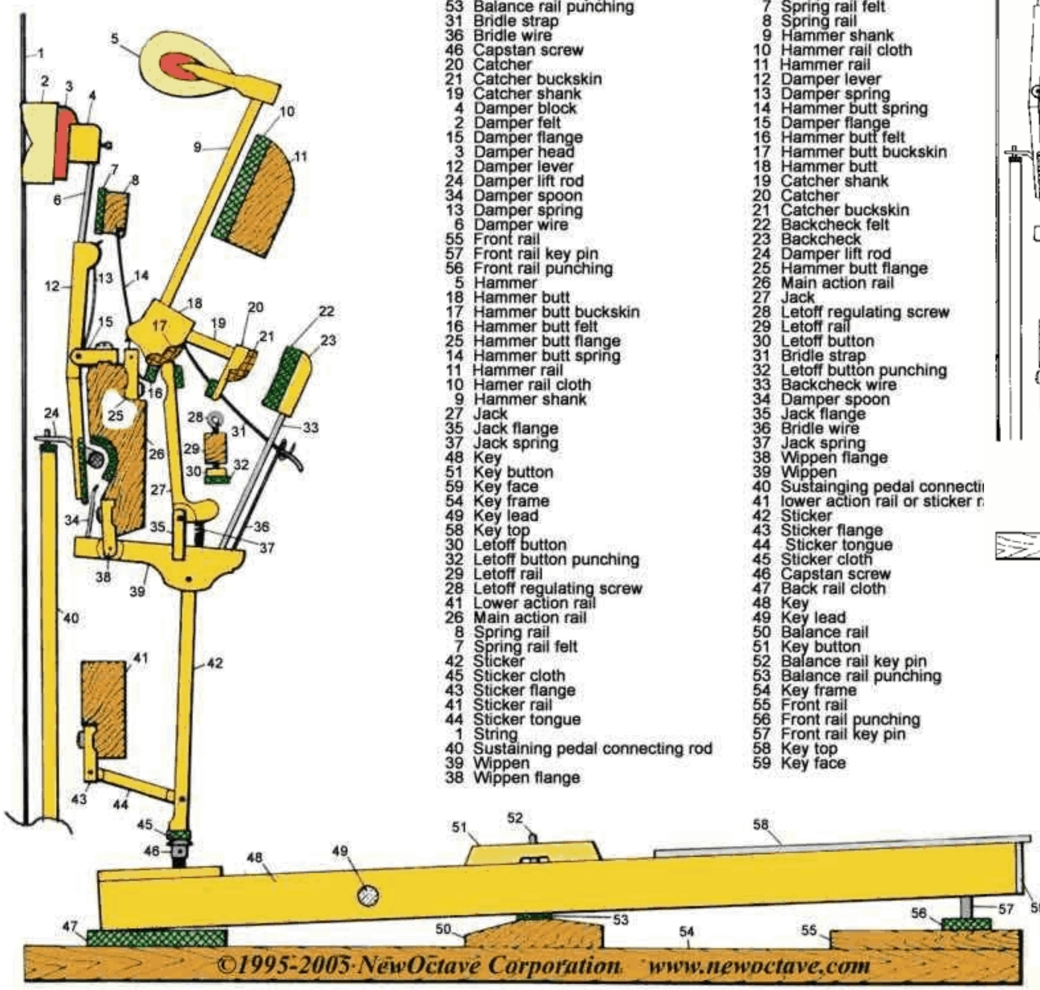
pianos were ***designed*** to be repairable
- likely need to remove 'action'

(if you break a string tuning it,
you'll need to remove the 'action' anyway)

(remember to number the keys before removing them
and mark which keys hit which strings)

"Regulation"
Fixing keys, and making mechanical adjustments
so they work optimally, and 'feel' uniform.

A clickable version of this image is now available at **pianoparts.com/upright**

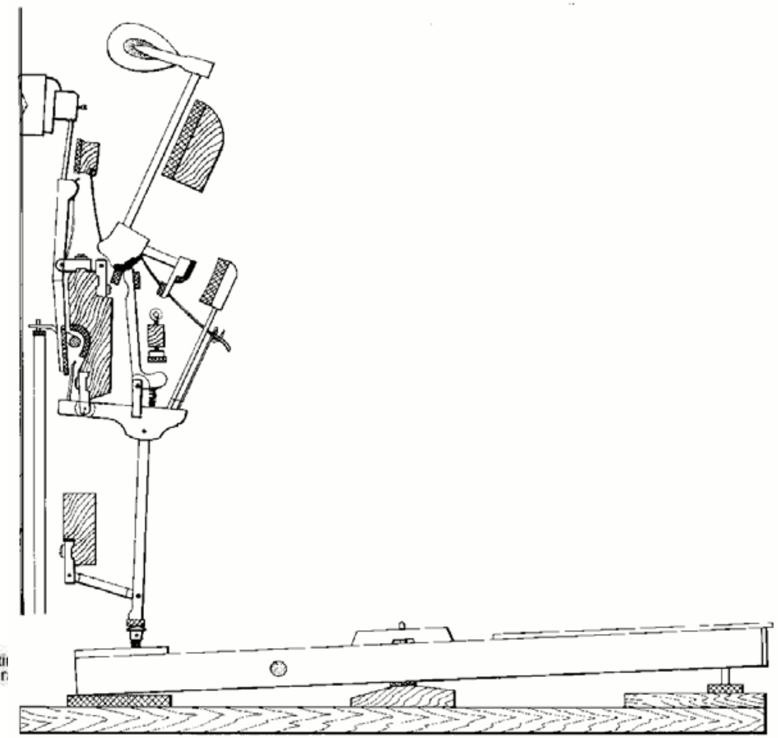


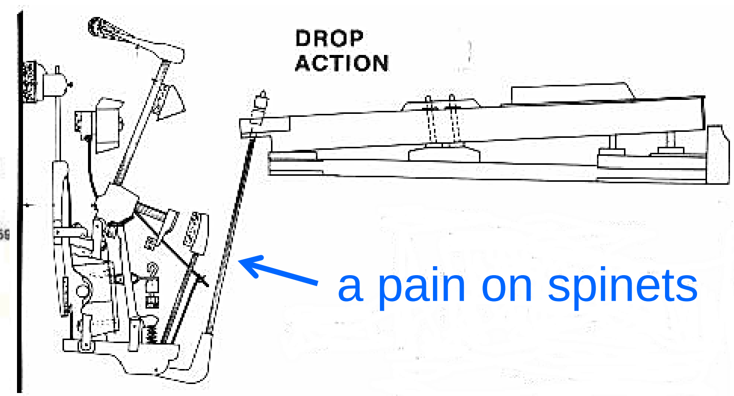
Alphabetically:

47 Back rail cloth
23 Backcheck
22 Backcheck felt
33 Backcheck wire
50 Balance Rail
52 Balance rail key pin
53 Balance rail punching
31 Bridle strap
36 Bridle wire
46 Capstan screw
20 Catcher
21 Catcher buckskin
19 Catcher shank
4 Damper block
2 Damper felt
15 Damper flange
3 Damper head
12 Damper lever
24 Damper lift rod
34 Damper spoon
13 Damper spring
6 Damper wire
55 Front rail
57 Front rail key pin
56 Front rail punching
5 Hammer
18 Hammer butt
17 Hammer butt buckskin
16 Hammer butt felt
25 Hammer butt flange
14 Hammer butt spring
11 Hammer rail
10 Hamer rail cloth
9 Hammer shank
27 Jack
35 Jack flange
37 Jack spring
48 Key
51 Key button
59 Key face
54 Key frame
49 Key lead
58 Key top
30 Letoff button
32 Letoff button punching
29 Letoff rail
28 Letoff regulating screw
41 Lower action rail
26 Main action rail
8 Spring rail
7 Spring rail felt
42 Sticker
45 Sticker cloth
43 Sticker flange
41 Sticker rail
44 Sticker tongue
1 String
40 Sustaining pedal connecting rod
39 Wippen
38 Wippen flange

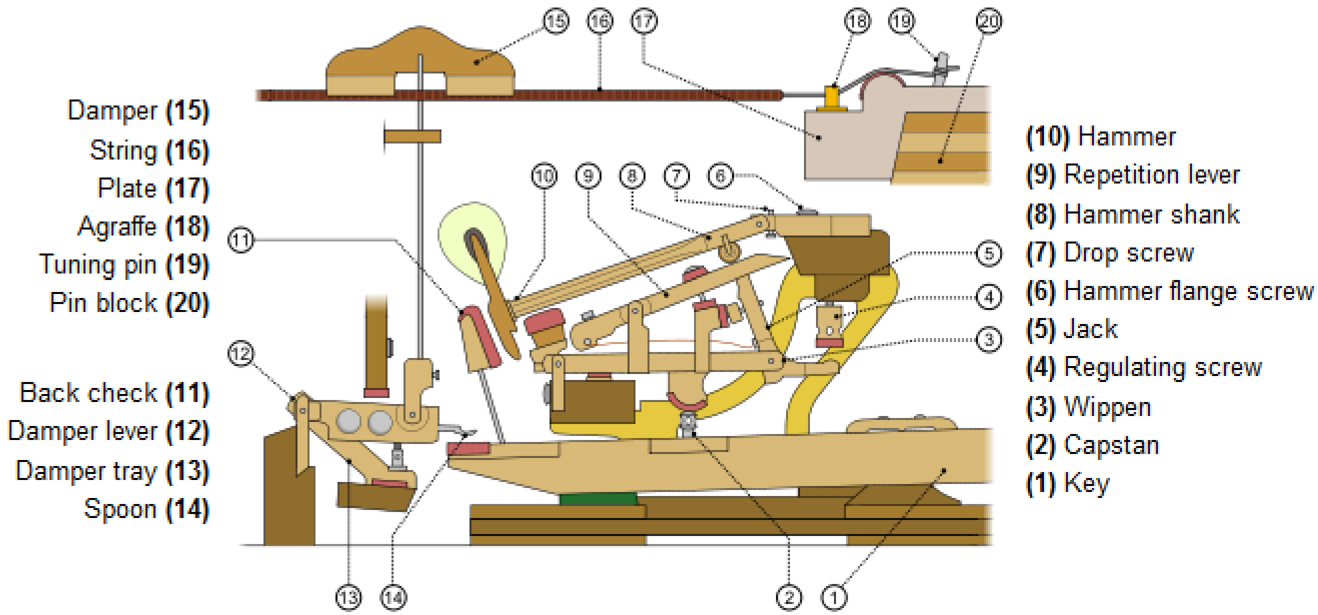
Numerically:

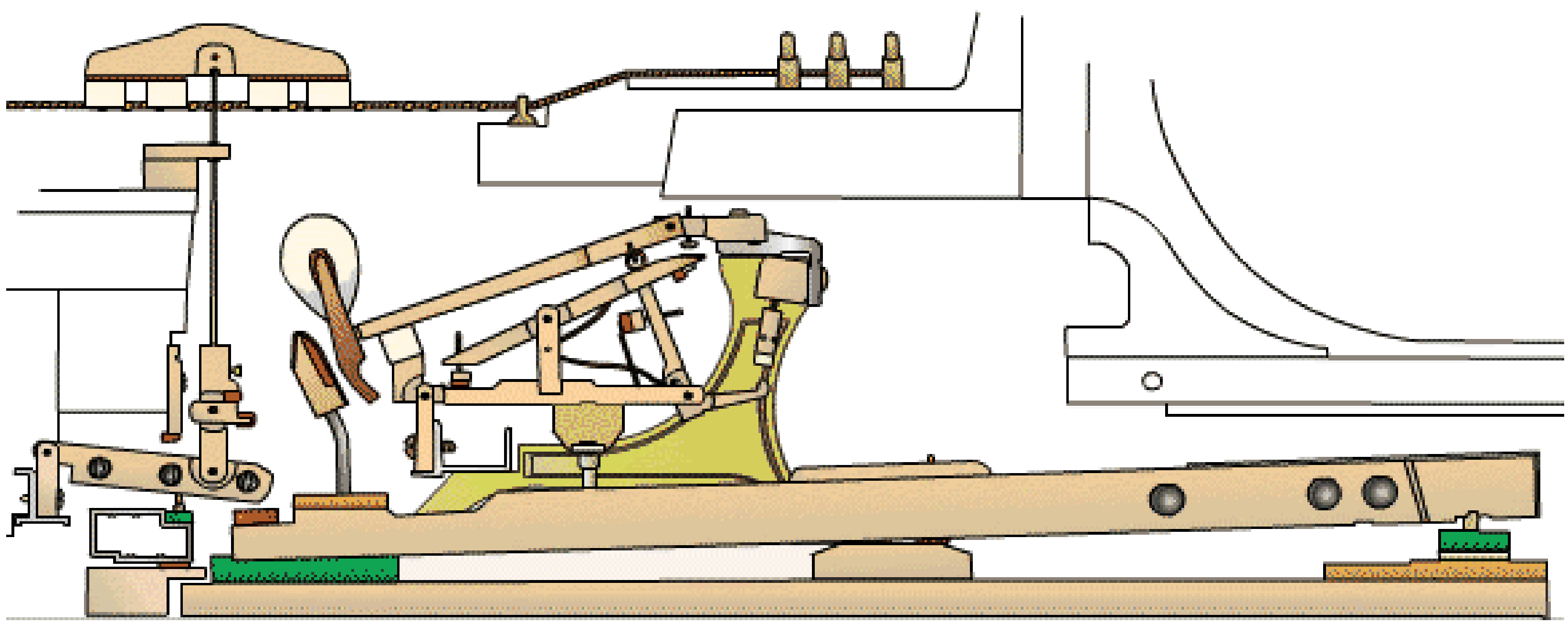
1 String
2 Damper felt
3 Damper head
4 Damper block
5 Hammer
6 Damper wire
7 Spring rail felt
8 Spring rail
9 Hammer shank
10 Hammer rail cloth
11 Hammer rail
12 Damper lever
13 Damper spring
14 Hammer butt spring
15 Damper flange
16 Hammer butt felt
17 Hammer butt buckskin
18 Hammer butt
19 Catcher shank
20 Catcher
21 Catcher buckskin
22 Backcheck felt
23 Backcheck
24 Damper lift rod
25 Hammer butt flange
26 Main action rail
27 Jack
28 Letoff regulating screw
29 Letoff rail
30 Letoff button
31 Bridle strap
32 Letoff button punching
33 Backcheck wire
34 Damper spoon
35 Jack flange
36 Bridle wire
37 Jack spring
38 Wippen flange
39 Wippen
40 Sustainging pedal connecti
41 lower action rail or sticker r
42 Sticker
43 Sticker flange
44 Sticker tongue
45 Sticker cloth
46 Capstan screw
47 Back rail cloth
48 Key
49 Key lead
50 Balance rail
51 Key button
52 Balance rail key pin
53 Balance rail punching
54 Key frame
55 Front rail
56 Front rail punching
57 Front rail key pin
58 Key top
59 Key face





Action of a grand piano





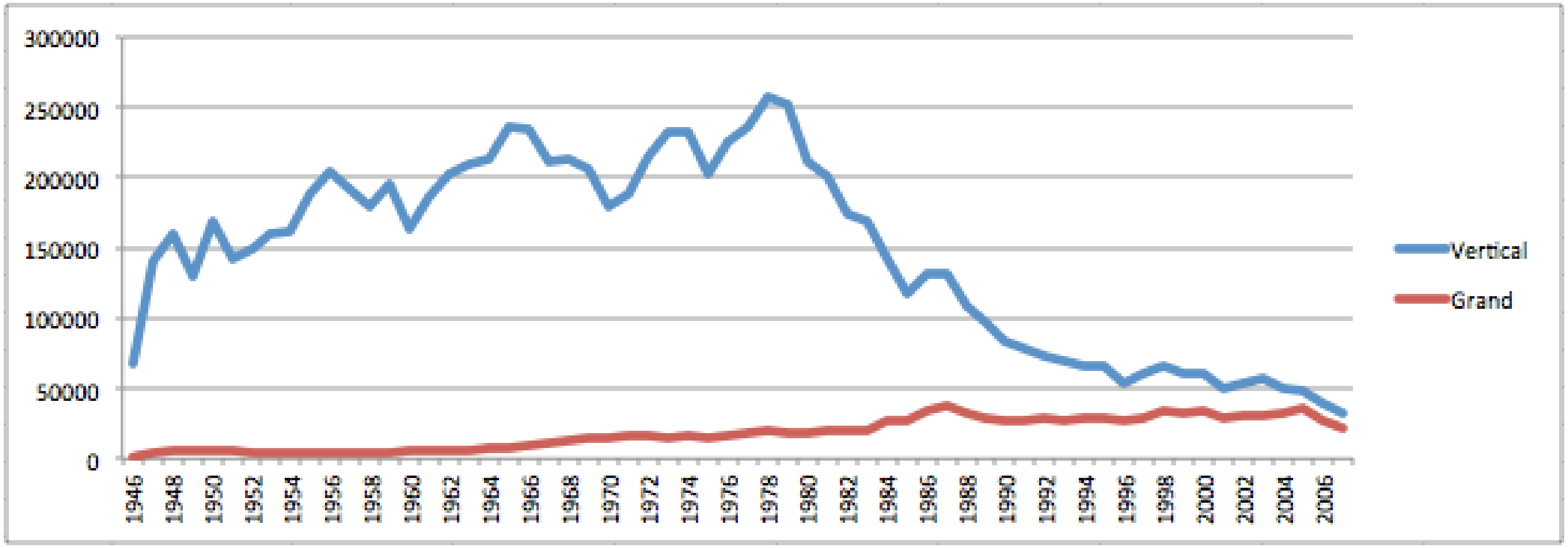
“Voicing” the hammers

NOT for the novice
(you can easily ruin a set of hammers)

Let's now do it for real…

pin turning
unisons ('true' or not?)
tune using FFTuner
put it back together

US Annual Piano Sales



getting harder to find…